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# Estimating Yield of Food Crops Grown by Smallholder Farmers

## A Review in the Uganda Context

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## INTERNATIONAL FOOD POLICY RESEARCH INSTITUTE

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## ABSTRACT

Precise agricultural statistics are essential for planning and evaluation of agricultural investments to improve the productivity and profitability of smallholder farming systems. However, accurately estimating crop yields is never easy and is even more of a challenge in the context of African farming systems that are characterized by smallholder farms that produce a wide range of diverse crops. With specific reference to yield estimation for food crops under smallholder farming conditions in Uganda, this paper evaluates the various methods that are available to estimate crop production and cropped area in such farming systems. A description and summary tables from a database of estimated crop yields in Uganda that was collated from a large set of field studies over past decades are also provided.

**Keywords: crop yield, smallholder farming, agricultural statistics, data collection**

# ACKNOWLEDGMENTS

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# 1. INTRODUCTION

## Background

Precise agricultural statistics are essential for policymakers, administrators, and scientists concerned with planning and evaluation of agricultural investments (de Groote and Traoré 2005). Their use includes monitoring of agricultural production changes, planning of agricultural interventions and development projects, development of early warning systems, and preparation of macroeconomic accounts (Murphy, Casley, and Curry 1991). Poor agricultural data can lead to misallocation of scarce resources and policy formulations that fail to resolve critical development problems (Kelly et al. 1995).

Accurately estimating crop yields is never easy and is even more of a challenge in the context of African farming systems that are characterized by smallholder farms that produce a wide range of diverse crops. Challenges that may occur include, among others, no cadastral information on land use (Murphy, Casley, and Curry 1991), intercropping, non-uniform plots in a wide range of sizes, not all planted area is harvested, and significant postharvest losses. Additional challenges in the Ugandan context include the mixture of seasonal crops (cereals, legumes) with crops that have an extended harvest period (banana, cassava, and coffee); the occurrence of a unimodal rainfall pattern in the north and a bimodal rainfall pattern in the rest of the country; and the habit of farmers to continuously plant their crops throughout the season or year as a result of an even rain distribution.

In Uganda, the Uganda Bureau of Statistics (UBOS) is responsible for supplying up-to-date agricultural statistics. It was formed in 1998 into a semi-autonomous institution from the Statistics Department of the Ministry of Finance, Planning, and Economic Development. UBOS aims to coordinate the development and maintenance of a national statistical system, which will ensure collection, analysis, and dissemination of integrated, reliable, and timely statistical information. UBOS carries out agricultural censuses to generate data on agricultural production, cropped area, and yields of the crops produced by Ugandan smallholder farmers. In addition, UBOS has added an agricultural module to their national household surveys.

To validate their agricultural yield data, UBOS requested the International Food Policy Research Institute (IFPRI), first, to review the methodologies that are in use to estimate agricultural yields under smallholder farming conditions globally and, second, to put together a database of crop yields in Uganda that have been estimated by a range of studies over the past decades. This report contains the methodological review and a concise summary of the crop yield information that was extracted from the developed database.

The next subsection provides an overview of the several concepts and terminologies that are used by different disciplines to discuss crop yield, while the following section, Section 2, gives an overview of the various methodologies that have been used in Uganda to estimate crop yields. Section 3 compares the two most common methods to estimate the crop production of smallholder farmers at the level of individual plots or farms: crop cuts and farmer estimates or recall. Section 4 discusses other methods that may be used to estimate crop production, whereas Section 5 focuses on the various methods that may be used to estimate the surface area of individual plots or farms. Section 6 discusses sampling and non-sampling errors and biases and puts these in a wider context, while Section 7 considers general issues that may complicate accurate estimation of crop yields. In Section 8, conclusions and implications for the Ugandan context are drawn from the discussion of the various methodologies that have been used globally to estimate crop yields.

The Appendix provides a description and summary tables from the database of estimated crop yields in Uganda that was collated from a large set of studies over the past decades. This database was a central output of the study under which this paper was developed.[1] Also provided in the Appendix are

[1] The crop yield database is available as a separate Excel file upon request from the IFPRI-Kampala office (IFPRI-Kampala@cgiar.org).

crop-by-crop narrative summaries of the yield information available for 10 crops commonly grown by Ugandan smallholder farmers.

## Definitions of Crop Yield

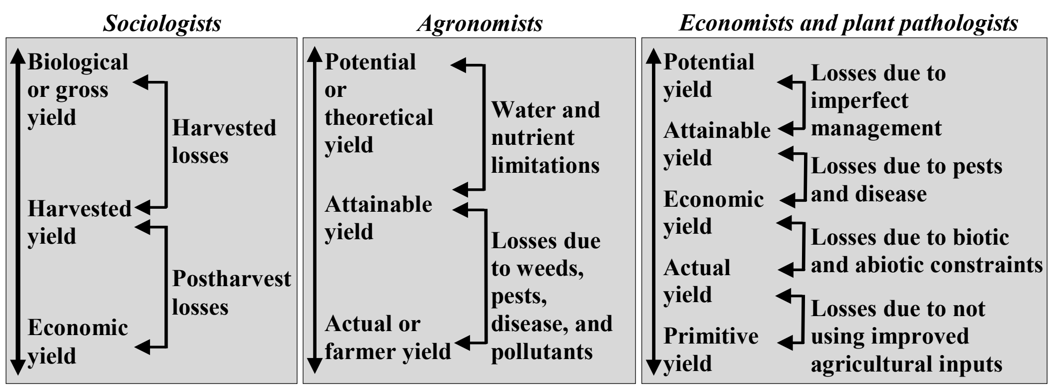
The World Bank (2010) in its global strategy to improve agricultural and rural statistics considers crop area, crop production, and crop yield as three key variables that should be part of the minimum core data set that all countries should be able to provide. It identifies crop productivity, or crop yield, as one of the essential indicators for agricultural development. In essence, crop yield is defined as

$$\text{Crop yield} = (\text{amount of harvested product}) / (\text{crop area}) \tag{1}$$

and is normally expressed as kilograms (kg) or metric tonnes (t) of product per hectare (ha). The estimation of crop yield thus involves both estimation of the crop area and estimation of the quantity of product obtained from that area. Though the definition seems simple, in many circumstances neither may be easy to estimate, both are prone to error and bias, and their measurement can be time consuming, as will be discussed.

In addition, various disciplines have developed their own concepts, approaches, and definitions to discuss crop yields. Confusingly, they sometimes use similar terminologies (for example, *economic yield*) with rather different definitions. Figure 1.1 gives an overview of the crop yield concepts that are generally used by sociologists, agronomists, and economists and plant pathologists, though concepts and terminologies may still vary within each group.

**Figure 1.1—Theoretical yield concepts by sociologists, agronomists, and economists and plant pathologists**




Source: Compiled by authors.

### *Yield Concepts of Sociologists*

Sociologists commonly use three distinct yield terminologies:

- *Biological yield* or *gross yield* is the yield obtained before any losses occur during and after harvest;
- *Harvested yield* is the biological yield minus harvest losses. Arguably, the quantity required as seed for next season's planting can be included in harvest losses (Poate, 1988); and
- *Economic yield*, which is the quantity that the farmer can use after postharvest losses that may occur during cleaning, threshing, winnowing, and drying have been taken into account (Casley and Kumar 1988; Keita 2003). Storage losses are normally not included in the definition of economic yield, though they may be important to the farmer.

### *Yield Concepts of Agronomists*

Agronomists commonly define three yield levels when modeling agricultural production and defining yield gaps:

- *Potential yield* or theoretical *yield* is the maximum yield that can be achieved in a given agroecological zone with a given cultivar. Production is determined solely by $CO_2$, temperature, solar radiation, and crop characteristics.
- *Attainable yield* takes into account growth limiting factors, such as nutrient deficiencies and water stress.
- *Actual yield* or farmer *yield* takes into account growth reducing factors, such as weeds, pests, diseases, and pollutants. This is the yield that farmers obtain under their current management (Rabbinge 1993).

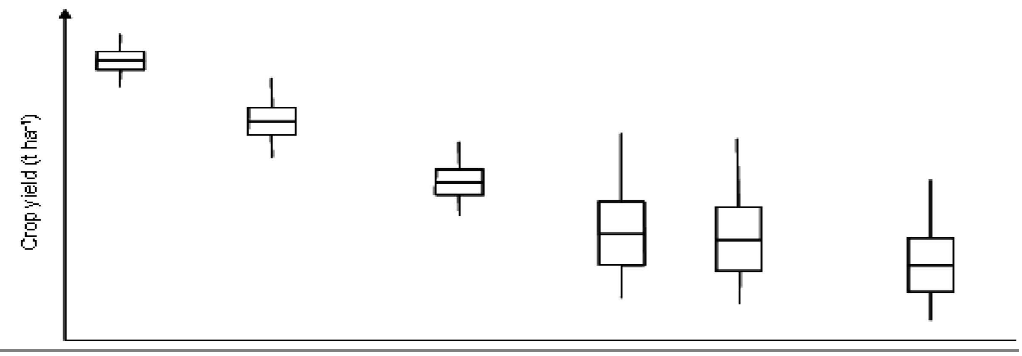
### *Yield Concept of Economists and Plant Pathologists*

Economists and plant pathologists commonly define five yield levels:

- *Potential yield* is the fullest expression of a specific crop genotype for a particular climatic environment in terms of ambient temperature and solar radiation.
- *Attainable yield* is the yield obtained using all available technology to minimize biotic and abiotic stress under experimental conditions.
- *Economic yield* is the yield level that provides highest financial returns to investment in addressing biotic and abiotic constraints to production.
- *Actual yield* is yield obtained due to partial use of available technologies.
- *Primitive yield* refers to the situation where none of the modern agricultural inputs are used (Hill 1987).

Figure 1.2 shows the relation between the crop yield terminologies used by the three paradigms and the range of relative yield levels that may be expected for each. The various methods that are used to estimate crop production for the different crop yield terminologies are indicated as well.

**Figure 1.2—Relation between crop yield terminologies used by sociologists, agronomists, economists, and plant pathologists; methods used to estimate each crop yield type; and relative range in crop yields in the field**




| | Yield terminology | | | | | |
|---|---|---|---|---|---|---|
| **Sociologists** | | | | Biological | Harvested | Economic |
| **Agronomists** | Potential | Attainable | | Actual or farmer | | |
| **Economists & plant pathologists** | Potential | Attainable | Economic | Actual | | |
| **Yield measurement methodology** | - Modeling | - Research station<br>- Maximum levels from on-farm trials | - On-farm input trials<br>- Economic modeling | - Crop cuts from subplots | - Entire field harvesting | - Farmer recall<br>- Total harvest weighing<br>- Sampling harvest units |

Source: Compiled by authors.

## 2. ESTIMATING CROP YIELDS IN UGANDA: A HISTORICAL OVERVIEW

The first serious attempt to estimate crop yields in the fields of Ugandan smallholder farmers was undertaken by the Ministry of Agriculture and Co-operatives in 1965 with the first agricultural census for Uganda. This was followed in 1967 with an agricultural survey collecting agricultural statistics on a subsample of the agricultural census. Though the aim was to do this on an annual basis, the annual surveys were abandoned after only two years. Due to political changes and civil strife, any plans for agricultural statistics gathering were then put on hold until the Ministry of Agriculture obtained resources to carry out an agricultural census in 1990/91. The Department of Statistics of the Ministry of Finance, Planning, and Economic Development and its successor, UBOS, implemented agricultural modules in 1995/96, 1999/2000, and 2005/06 as part of the Uganda National Household Survey (UNHS) program. In 2008/09, a third agricultural census was carried out by UBOS, with the support of the Ministry of Agriculture, Animal Industries, and Fisheries (MAAIF). Details on the various censuses and surveys that estimated crop yields are given in Table 2.1 and in the following paragraphs.

### Agricultural Censuses

#### *Agricultural Census of 1965*

The 1965 agricultural census collected data from about 1,200 farmers and 4,500 plots that had been randomly chosen from 90 parishes in 14 districts (MAC 1967). Crop yields for maize, sorghum, millet, banana, sweet potato, groundnuts, and beans were determined on the basis of daily recording. Both yield data for pure stand and intercropped plots were collected. To reduce the workload of the enumerators, data collection was limited to two-to-three crops per district. As not all selected farmers had planted the crops under study, the number of surveyed plots per district and per crop was extremely low in some cases, ranging from 20 to 120 observations in the majority of cases, with a maximum of 200 to 250 plots in a few cases.

The sample plot area was determined directly after planting using the rectangulation and triangulation method, and the crops grown in the plot were recorded. At each visit, the enumerator weighed any crop produce harvested by the farmer since the previous visit in the standard weight unit, kilograms (kg). The local state of harvest was indicated as wet or dry, with stalk or without, with shell or without, or indicating another state. If possible, for each crop two or three samples were taken during the survey period and weighed after harvesting and again after postharvest processing and drying to determine a conversion factor. The obtained conversion values were averaged at national level per crop and per state of harvest.

#### *Agricultural Census of 1990/91*

For each crop, the 1990/91 agricultural census collected data from a maximum of 40 randomly selected plots per district (2 per sub-parish) in a total of 26 districts (MAAIF 1992) Crop yields were determined on the basis of crop cuts using the planted area as the crop area. Data were collected for all staple foods, except rice. Though the census distinguished pure stand and intercropped plots in the crop area survey, no such distinction was made for the crop yield survey.

**Table 2.1—Details on the agricultural censuses of 1965, 1990/91, and 2008/09; the annual agricultural surveys of 1967/68 and 1968; and the agricultural modules of the Ugandan National Household Surveys (UNHS) in 1995, 1999, and 2005/06**

| | Plots or HH, no. | Enumeration areas, no. | Stratification | Production estimation | Area estimation | Pure stand vs. mixed stand | Yield concept | Notes |
|---|---|---|---|---|---|---|---|---|
| **Agricultural Censuses** | | | | | | | | |
| 1965 | 4,500 plots | 90 | 1. District (14)[a]; 2. Parish (no. adult men); 3. Farming household | Daily recording | Rectangu-lation and triangu-lation | Separate yield data for pure stand and mixed stand | Economic yield | Yields were collected for 2 to 3 crops per district in separate surveys. State of harvest recorded. Average conversion factors developed at national level Observations on up to 235 plots per crop by district. |
| 1990/91 | 1,040 plots | 520 | 1. District (26)[b] 2. Sub-parish (no. tax-payers) 3. Crop plots | Crop cut | 3 x 3m; 5 x 5 m, or 10 x 10 m subplots | No details, most likely pure stand only | Biological yield | Maximum of 40 plots per crop per district surveyed. State of harvest recorded. Use of conversion factors is unclear. |
| 2008/09 | *Not yet documented* | *Not yet documented* | 1. District 2. Sub-county 3. Farming household | Farmer recall; Crop cards | Farmer recall | *Not yet documented* | Economic yield | Details on 2008/09 agricultural census not yet documented. |
| **Annual Surveys** | | | | | | | | |
| 1967/68 | More than 9 per district | 78 | 1. District (14)[a] 2. Parish 3. Crop plot | Crop cut | 3 x 3 yard subplots | Separate yield data for pure stand and mixed stand | Biological yield | Unclear on how many plots the crop yield estimates were based (at least 9 plots per district). Likely, the unit conversion factors that were determined in the 1965 agricultural census were used in the annual surveys. |
| 1968 | | 76 | | | | | | |
| **Uganda National Household Surveys (UNHS)** | | | | | | | | |
| 1999 | 8,400 households | 1,083 | 1. Region 2. Enumeration area 3. Farming household | Farmer recall | Farmer recall | No details | Economic yield | Yield estimates are not distinguished according to pure or mixed stand, although the percentage of pure stand plots is indicated at regional level. |
| 2005/06 | 5,877 households | 753 | 1. Region 2. Enumeration area 3. Farming household | Farmer recall | Farmer recall | No details | Economic yield | Yield estimates are not distinguished according to pure or mixed stand, although the percentage of pure stand plots is indicated at regional level. |

Source: Compiled by authors.
Notes: [a] West Mengo, East Mengo, Mubende, Masaka, Busoga, Bukedi, Bugisu/Sebei, Teso, Kigezi, Ankole, Bunyoro, Lango, Acholi, and West Nile/Madi
[b] Apac, Arua, Bundibugyo, Bushenyi, Hoima, Iganga, Jinja, Kabale, Kabarole, Kamuli, Kapchorwa, Kasese, Lira, Luwero, Masaka, Masindi, Mbale, Mbarara, Moyo, Mpigi, Mubende, Mukono, Nebbi, Rakai, Rukungiri, and Tororo

The estimated crop yields most likely are based on pure stand plots, though this is not indicated in the census report. Within each plot, one subplot was randomly selected and laid out far in advance of harvesting the plot. Subplot size was 3 x 3 meters (m) for cereals (except for maize), oil seeds, and legumes, 5 x 5 m for maize and cassava, and 10 x 10 m for banana. Enumerators were expected to harvest the subplots at the same time as the farmers. In case the farmer harvested the crop gradually over time, the enumerator was instructed to do the same in the subplot and add up the weights of the individual harvests. However, for cassava and banana, the enumerators were instructed to only record one harvest, which was extrapolated into an annual crop yield figure. Both fresh and dry weights after processing were recorded on a 25 kg weighing scale and the state of harvest for both the fresh and processed weights were indicated as one of the following: with shell, without shell, with stalk, without stalk, in the cob, seeds, and specified other. The 1990/91 census reports remain vague on whether any conversion factors were used to convert the processed weight to a standard state of harvest, and, if so, how these were obtained. Average crop yields are presented per district without details on the number of crop cuts they were based on and whether they were obtained from pure or mixed plots.

### *Agricultural Census of 2008/09*

The sample for the 2008/09 agricultural census consisted of more than 35,000 agricultural households selected from all of the then 80 districts of the country. Information was also collected from more than 2,000 private large-scale or institutional farms. Crop yields were determined on the basis of farmer recall data from all enumerated farmers. In addition, the 2008/09 census used the crop card method to obtain yield data for crops with an extended harvest period.

## Annual Agricultural Surveys

In the annual agricultural surveys that were conducted in 1967/68 and 1968, 19 enumerators collected yield data in 78 and 76 parishes, respectively, that were randomly selected from 14 districts (MAF 1969). Crop yields were determined on the basis of crop cuts. For each crop, yield results are based on at least nine randomly selected plots per district. A subplot size of 3 x 3 m was used for all crops, and data were obtained for both pure stand and intercropped plots. Data were collected for maize, sorghum, millet, groundnuts, and beans only. Though not indicated in the survey report, enumerators likely indicated the state of harvest in the field, with results converted to a standard state of harvest using conversion factors that were determined during the implementation of the 1965 agricultural census.

## Uganda National Household Surveys

In order to regularly collect statistics on agriculture in Uganda, UBOS includes an agricultural module to every other national household survey, rotating the agricultural module with a labor force module. The UNHS surveys are carried out every two years, on average. The 1999 and 2005/06 UNHSs collected data from 8,400 and 5,877 households, respectively, that were randomly selected from 1,081 and 753 enumeration areas, respectively, which were, in their turn, randomly selected from the four main regions in Uganda as the survey strata. Crop yields were determined on the basis of farmer recall. Data were collected for all major staple food crops. No distinction was made between crops grown as a pure stand and as intercrops, though the percentage of plots grown as a pure stand was indicated for each crop.

## 3. ESTIMATING CROP PRODUCTION: CROP CUTS AND FARMERS ESTIMATES

As pointed out in the introduction, the estimation of agricultural yields is based on the ratio of estimated crop production and estimated crop area. Crop cuts and farmer estimates are the two methodologies most commonly used by scientists and statisticians to estimate crop production. This section first discusses some methodological details on each and then presents the results of studies that compare the two and discusses the biases that have been observed. Conclusions are then presented on the appropriate use of crop cuts and farmer estimates.

### Crop Cuts

In the late 1940s, pioneers in sampling and survey design developed a method for estimating crop yields based on sampling of small subplots within cultivated fields in India. In the 1950s, these so-called crop-cut methods quickly were adopted as the standard method recommended by the Food and Agriculture Organization of the United Nations (FAO) to measure crop production (FAO 1982; Murphy, Casley, and Curry 1991). Crop cuttings may involve measurements in a central plot or in one or more subplots. Crop yield is calculated as total production divided by total harvested area in the crop cut plot or sub-plots. Before harvesting, enumerators should agree on which products are harvestable and which are not. Examples of products not harvested include smut-affected cereal heads or cobs, unripe products, or undersized products. Agreement should also be reached on what type of drying and shelling process is used, if appropriate. Crop cuts are commonly used to estimate crop yields in on-station and on-farm trials, detailed farm surveys, and on-farm demonstration plots.

#### *One Random Subplot*

The original crop-cut method was based on harvesting one random subplot in each farm field. The method involves randomly locating prior to the harvest of a small subplot, usually a square or a triangle, within each field. At the time of harvest, the subplot is harvested by the survey enumerator, the crop is dried and processed, and then it is weighed. A derivative of this method is the yield plot method, described by Spencer (1989). In this case, the enumerator stakes out a randomly chosen quadrant in a farm field before harvest. When the farmer harvests his or her plot, he or she leaves the quadrant unharvested, which is cut and measured by the enumerator soon afterward.

#### *Two Large Quadrants*

As one randomly chosen subplot may not represent the variability in crop performance within a field, Fielding and Riley (1997) suggest using two large quadrants (in the order of 50–75 $m^2$ each). The use of two subplots builds in a check on the reliability of harvest data and also allows highlighting of peculiar values.

#### *Multiple Small Quadrants*

To take into account staggered ripening and harvesting of cereals, Norman et al. (1995) suggest using a systematic sampling scheme with multiple small quadrants. This method is based on a study in Botswana showing that variability in grain yields is more related to variability in the number of heads/cobs per hectare than to variability in average weight per head or cob. In each plot, 20 subsamples from 2 x 2 m quadrants are taken in a systematic way. In each quadrant the number of heads/cobs already harvested (HR), the number of heads/cobs ready for harvest (MT), the number of heads/cobs that are green and can still reach maturity (GR), and the number of heads/cobs lost to cattle (CZ) is counted. All MT heads/cobs are harvested, dried, and threshed and average grain weight per head is calculated. Total yield is determined, assuming HR, GR, and CZ heads/cobs have a similar average weight. The method may be adapted to indeterminate grain legumes. Intercropping can be taken into account by taking separate data on each observed crop.

A second, less-intensive, multiple quadrant crop-cut method is the so-called "five-point" method, whereby the enumerator harvests five one-square meter quadrants located in the corners and the center of a plot (Rozelle 1991).

### *Sub-sampling Using Row Segments*

To facilitate logistics and ease of operation, the multiple small quadrant method can be simplified by using a measuring stick instead of a quadrant (Norman et al. 1995). The same observations as above are made in a number of row segments that are the length of the measurement stick. However, harvest data from the quadrant method are more reliable because subplot boundaries are clearer. This was confirmed by Verma et al. (1988), who reported in a detailed study in five countries that quadrant sampling gave more accurate results than row sampling.

## Farmer Estimates

Estimating crop production through farmer interviews involves asking farmers to estimate for an individual plot, field, or farm what quantity they *did* harvest or what quantity they *expect* to harvest. The first is commonly known as farmer recall, whereas the second is referred to as farmer prediction. As harvest quantities are farmer estimations, they are generally expressed in local harvest units instead of kg or tonnes. To convert harvest quantities to standard units, conversion factors will be required.

### *Farmer Recall*

Postharvest estimations are commonly made at the farmer's house or at the site where the harvest is stored in order for the enumerator to cross-check the estimates with the available storage capacity (Casley and Kumar 1988). Recall periods may range from six months or one season to three years or three-to-six seasons, depending on rainfall distribution (Howard et al. 1995; Lekasi et al. 2001; Erenstein, Malik, and Singh 2007). Instead of asking farmers to estimate harvested quantities for individual growing seasons, Smale et al. (2010) give examples of longer-term subjective recall, two-year average production data, for example, or minimum, maximum, and average production for years with or without drought stress. Developed countries, such as Sweden, are increasingly obtaining farmer recall data through web-based surveys or telephone interviews (pers. comm., G. Ländell, Sweden Statistics, 2010).

To estimate crop yield, production data obtained from farmer recall require division by the plot area from which the crop was harvested. This introduces an additional source of error. To remove this error source, Fermont et al. (2009) obtained a direct estimate of average crop yield by asking farmers to estimate the number of local harvest units they would have obtained from a well-known unit of land, often the farm compound, if it had been planted to a specific crop.

### *Farmer Prediction*

Pre-harvest estimations are commonly obtained on a plot-by-plot basis, whereby the enumerator and the farmer are in visual contact with the growing crop. The enumerator may thus be able to judge the validity of the farmer's response. Farmers will base their predictions of expected yield on previous experiences, by comparing the current crop performance to previous crop performances (David 1978). According to Singh (2003), yield estimations should be made at maximum crop growth. In the United States, monthly telephone interviews are conducted with farmers to obtain production forecasts (USDA 2009).

## Comparing Crop Cuts and Farmer Estimates

Since the endorsement of the method by the FAO in the 1950s, crop cuts have been commonly regarded as the most reliable and objective method for estimating crop yields: a sufficient number of cuts in a sufficient number of fields will provide a valid estimate of average yields (Murphy, Casley, and Curry 1991). A strong advantage of the crop-cut method is that the area of the cut is known and thus does not introduce an error into the final yield computation (Poate 1988). Crop cuts measure the *biological yield*. They do not take into account any postharvest losses and thus do not reflect the *economic yield* that is of use to the farmer. The most common alternative for crop cuts is the use of farmer estimates, which gives a measure of economic yield.

Obtaining yield estimations through crop cuts is both time and labor-intensive. To facilitate field work and reduce costs and time, a clustered sampling procedure is therefore normally applied when crop cuts are used for larger scale surveys. In contrast, the use of farmer estimations does not require laborious measurements and allows for a more efficient, random sampling design (Murphy, Casley, and Curry 1991; Casley and Kumar 1988). Compared to crop cuts, the use of farmer estimations is thus a cheap and quick method that saves time and money. Consequently, with the same resources farmer estimations allow for a larger number of yield estimates to be collected than crop cuts.

For years, it was assumed that farmer estimates were too subjective and unreliable to obtain reliable data on crop yield (Verma et al. 1988), whereas crop cuts were assumed to be unbiased (Murphy, Casley, and Curry 1991). Thus, when farmer estimates differed from crop-cutting measurements, it was automatically assumed that the differences reflected “farmer error.” The idea that crop-cut measurements were not seriously affected by bias (such as consistent over- or underestimation) was based on early evidence from crop-cut work in India. However, in the late 1980s evidence started emerging that biases associated with crop cuts are often substantial. Especially in the case of small, irregularly shaped fields with uneven plant density, biases were found to be large, which is the situation of many smallholder farmers in Africa (Murphy, Casley, and Curry 1991; Poate 1988). At the same time, however, several studies showed that the use of farmer estimates also has its own problems with respect to bias.

Several studies specifically compared yield or production estimates obtained from crop cuts with estimates from farmer recall or farmer prediction. In some cases both estimates were compared to whole plot harvests as an ‘objective’ reference level, in other cases not. With the crop-cut method measuring biological yield, the whole-plot-harvest method measuring harvested yield and the farmer recall method measuring economic yield all methods take into account different amounts of harvest losses. Therefore, theoretically, the three yield estimates obtained for the same plot can never have the same value. If all estimates are completely free of sampling and non-sampling errors, the estimated yield levels should be in the following order: crop cuts > whole plot > farmer recall (see Figure 1.2).

### Comparison with Objective Reference Level

Casley and Kumar (1988) report for a small and controlled survey in Nigeria, which compared crop-cut estimates obtained from 60 $m^2$ subplots with farmer predictions and whole plot harvests of millet and sorghum. They found an average bias of 14 percent for both crop cuts and farmer predictions. The same authors quote a study on rice in Bangladesh that showed that crop cuts had an average 20 percent upward bias, compared with whole plot harvests, while a small study in Bangladesh quantified the bias in farmer recall data at 15 percent (Poate 1988). A small study using precise procedures on soybeans in the United States showed that the bias in yields estimated using crop cuts may be as low as 5 percent. In some cases in this study, the crop cuts even underestimated yields, compared with whole plot harvesting (Rogers and Murfield 1965).

The largest study comparing crop cuts and farmer estimates to whole-plot reference harvests was done by Verma et al. (1988). The study was carried out in five African countries and compared whole plot harvests of 100 to 120 maize or millet plots per country with (1) crop-cut estimates from two 25 $m^2$ subplots; (2) farmer predictions obtained two-to-four weeks before harvest; and (3) farmer recall obtained zero-to-three weeks after harvest. Results are presented in Table 3.1. The crop-cut method resulted in serious overestimates of production in all countries. Only in Zimbabwe was the error as low as 14 percent and of the same order of magnitude as the studies reported by Casley and Kumar (1988) and Poate (1988). In the other four countries, the overestimation was in the range of 25 to 38 percent. The bias in farmer predictions varied widely from −27 percent in the Central African Republic to +43 percent in Zimbabwe. Notably, the bias in estimates from farmer recall was within 10 percent in each country, with an overall combined error of only 3 percent. The mean farmer recall estimates not only were closer to the actual recorded production, but they also displayed considerably less variance.

**Table 3.1—Percentage of over- and underestimation of production estimates obtained with crop cuts, farmer prediction, and farmer recall, compared with whole plot harvest of maize and millet fields in five African countries**

| Country | Crop cut | Farmer prediction | Farmer recall |
|---|---|---|---|
| Benin | 25 | 19 | -8 |
| Central African Republic | 31 | -27 | 7 |
| Kenya | 38 | 2 | 1 |
| Niger | 32 | 20 | - |
| Zimbabwe | 14 | 43 | 7 |
| **Overall** | **34** | **9** | **3** |

Source: Verma et al. (1988).

In contrast to the above study, Rozelle (1991) reports that Malawian farmers had great difficulties estimating crop production after harvest. Diskin (1997) points out that Verma et al. evaluated production estimates, not crop yield estimates. Thus their study only provided evidence of the merits of farmer estimations over crop cuts when estimating production not yield. Converting production estimates to yield estimates requires dividing the production estimates by area estimates. Diskin (1997) argues that the results of Verma et al. only support the use of farmer interviews over crop cuts to estimate crop yields in cases where farmer estimates of area have a minimum source of error.

### *Comparison without Objective Reference Level*

Casley and Kumar (1988) present data from the Central Statistical Office in Zimbabwe that compare crop cuts with farmer estimates of yields on smallholder maize fields for two consecutive years across six regions (Table .2). Crop-cut estimates were on average 86 percent (with a range of 32 to 100 percent among regions) higher than farmer estimates. In the second year, supervision of the crop cuts was much tighter. Nonetheless, crop-cut estimates were on average 37 percent (with a range of 27 to 78 percent between regions) higher than farmer estimates. Though this shows that crop cuts likely overestimate crop yields, it does not rule out a substantial margin of bias in farmer estimates.

**Table 3.2—Comparison of yield estimation methods in maize yields (t/ha) in smallholder fields in six regions in Zimbabwe in two growing seasons, 1984/85 and 1985/86**

| | 1984/85 | | | 1985/86 | |
|---|---|---|---|---|---|
| Region | Crop-cut | Farmer estimate | Extension estimate | Crop-cut | Farmer estimate |
| Manicaland | 3.4 | 1.8 | 1.9 | 1.5 | 0.9 |
| Mashonaland Central | 5.1 | 2.6 | 2.9 | 4.0 | 2.8 |
| Mashonaland East | 4.4 | 2.3 | 2.2 | 2.8 | 2.1 |
| Mashonaland West | 3.5 | 1.9 | 2.1 | 3.0 | 2.2 |
| Midlands | 3.3 | 2.5 | 2.7 | 3.2 | 2.1 |
| Masvingo | 3.4 | 1.7 | 1.8 | 1.3 | 1.0 |
| Unweighted average | 3.9 | 2.1 | 2.3 | 2.6 | 1.9 |

Source: Casley and Kumar (1988).

This Zimbabwe study is in line with a study by Minot (2008) in Ethiopia. He reported that average cereal yields in 2008 as determined with crop cuts in an agricultural sample survey of the Ethiopian Central Statistical Agency were 31 to 46 percent higher than farmer yield estimates for the same season as observed in a large household survey carried out by IFPRI.

In contrast to these African studies, a five-year study from Statistics Sweden showed first, that farmer recall did not systematically underestimate cereal yields and, second, that farmer estimates did not strongly deviate from the cereal yields observed with crop cuts (-4.9 to +9.5 percent) at country level (Hagblad 1998). However, it is possible that Swedish farmers may be better able than African farmers to recall production due to the higher levels of mechanization, commercialization, and record keeping within Swedish farming systems.

Various other studies compare farmer prediction (as opposed to farmer recall) with crop cuts. In two studies in Asia, crop cuts were strongly correlated ($R^2 = 0.86$) to farmer predictions of rice yields but 25 and 37 percent higher (David 1978). This is in line with results from India, where farmer predictions of wheat yield were also strongly correlated ($R^2 = 0.87$) to crop-cut yield data (Singh 2003).

## Sources of Bias

Both the crop cut and the farmer recall methods are affected by a range of inherent biases, which have been discussed by many authors. Bradbury (1996b) argues that in both cases the quality of the crop yield data likely suffers more from the consequences of bias than from sampling errors.

### *Sources of Bias in Crop Cuts*

Reported sources of bias in crop-cut estimations include (Fielding and Riley 1997; Murphy, Casley, and Curry 1991; Casley and Kumar 1988; Poate 1988; David 1978):

- *Edge effect.* Inclusion of plants in the measurement area that actually falls outside it. This is especially a problem in broadcast sown or randomly planted fields. The edge effect depends on the ratio of the perimeter to the area of the subplot and thus on its size and shape. Circles and squares have a smaller effect than triangles. The edge effect may give an upward bias of 2 to 3 percent for larger plots (greater than 25 $m^2$), but may be much higher (30 to 40 percent) in small plots (1 to 2 $m^2$).
- *Border effects.* The tendency for the border of the plot to have a lower chance of inclusion in the measurement area because of the rules governing location. As yields near the field border are commonly lower than in the center of the plot, an upward bias of less than 5 percent is introduced.
- *Nonrandom location of subplots.* Enumerators have an almost unavoidable tendency to consciously or unconsciously avoid low-yielding areas within plots when locating subplots, while this is not the case with lush parts of the plots. Especially under extensive cultivation, farmer fields often express an enormous heterogeneity. The upward bias resulting from nonrandom location of subplots can therefore be very substantial, especially if carried out by extension workers that want to show results of their work.
- *Harvest effects.* Field workers have a tendency to harvest crop cuts more thoroughly than farmers would. This upward bias can be reduced by discussing with the survey field workers what product is harvestable and what should not be harvested (for example, smut-affected cereal heads or very small tubers).
- *Weighing problems.* The use of inappropriate weighing scales (such as a 25 kg scale to record weights of less than 5 kg), faulty weighing scales, and basic weighing problems, such as not deducting the weight of the measurement container from the gross weight to obtain net weight (taring) where weights are small may introduce important measurement errors.

Except for the last one, these effects all result in an upward bias, whereby the overestimation bias increases with decreasing plot size. Although individual errors may be small, the combination of errors can be significant (Murphy, Casley, and Curry 1991). Consequently, crop cuts invariably result in overestimation of economic crop yield, typically by the order of 30 percent, but overestimation can be as high as 80 percent.

In addition to the above sources of bias, various authors (Casley and Kumar 1988; Diskin 1997) report other problems associated with crop cuts. These include

- *Heterogeneous crop performance.* Crop performance in smallholder fields is often enormously heterogeneous due to the presence of tree stumps and termite hills, varying spatial arrangement of crops, variability in soil quality within a field, and animal damage. Crop-cut data therefore commonly have high variance: within field yield variation is commonly 40 to 60 percent.
- *Costly and time consuming.* The enumerator needs to be present to weigh the crop when the farmer is ready to harvest. This makes the method rather costly and time consuming.
- *One point in time observation.* Crop cuts are obtained at one point in time, thereby not taking into account ripening and harvesting over time. This results in an underestimation of crop yields.

### *Sources of Bias in Farmer Estimates*

Although farmer recall and predictions were found to give more accurate and less variable estimations of production than crop cuts in several studies, and they are definitely easier and less costly to carry out, they too have their disadvantages. These include the following types of measurement and response errors.

- *In-kind payments.* Farmers use part of their production as in-kind payments to laborers and as gifts to family and friends. According to David (1978), farmers may forget to include these in-kind payments and gifts in their production estimates, especially when the hand out is done before storing the harvest. This may result in yield underestimations of 3 to 9 percent.
- *Nonstandard harvest units.* The type of local harvest unit and their average weight may vary considerably between regions, years, and even farmers (Diskin 1997). In Nigeria, a bundle of sorghum was found to weigh up to twice as much in one region as in another region, while the coefficient of variation within a region ranged between 18 and 70 percent (Casley and Kumar 1988). The use of one "average" correction factor for each local harvest unit may thus result in serious errors in crop production and yield estimates in large-scale or national surveys.
- *Conscious over- or underreporting.* Farmers may systematically over- or underreport production data in case of suspected benefits, such as food aid or a free input program, or penalties, such as taxes (Poate 1988; Diskin 1997). Farmers in an improved maize technology project in Mozambique, for example, underreported maize yields, hoping for partial forgiveness for an input loan they received (Jeje et al. 1998). In Sweden, potato yield estimates from farmer recall were 19 percent lower than crop cuts, presumably because farmers tried to positively influence potato prices (Hagblad 1998). But there is a vast pool of experience demonstrating the openness of African smallholders if approached in a proper manner (Murphy, Casley, and Curry 1991). When farmers see themselves as participants in a survey and understand its objectives, they feel less suspicious and are more motivated to give accurate figures.

- *Low accuracy with longer recall periods.* Recall data obtained from several seasons or years may not be very accurate because farmers may have forgotten season-specific details or may mix up events (Ali et al. 2009). Farmer recall data in two large Ethiopian surveys carried out within six months of each other were only moderately correlated ($R^2$s between 0.4 and 0.7), suggesting that farmer recall quality may have deteriorated over time (Howard et al. 1995).
- *Historical average production factors*. Farmers may report historical average production figures for their crops instead of specific production in the last season or year (Rozelle 1991).
- *Poor quality responses in lengthy interviews*. In cases when farmer recall data are obtained from lengthy interviews, the farmer may get tired and give superficial answers in order to avoid prolonging the interview (Casley and Kumar 1988; UBOS 2002). The same factor may motivate the enumerator to not conduct the interview as expected. In cases of lengthy interviews, the enumerator may also get tired and feel less motivated to cross-check answers or probe deeper.
- *Insufficient supervision***.** As farmer recall surveys are generally carried out with a large number of farm households, strict supervision of the enumerators may be impossible. This may affect data quality as enumerators are not corrected for sloppy work.
- *Illiteracy*. Especially in Africa, high levels of illiteracy among smallholder farmers may compromise data quality, as such farmers are unable to keep farm records (Kelly et al. 1995).
- *Inherent lack of knowledge*. An inherent lack of knowledge on the farmer's side may result in inaccuracies (Casley and Kumar 1988).

The last two reported disadvantages of the farmer recall method may not be very valid as Poate (1988) argues that it is hard to believe that a farmer would not know his or her harvested output, since their farm production is critical to the material survival of the farming household.

As mentioned before, crop performance in smallholder farming systems is highly heterogeneous, both within plots and between plots, villages, and regions. Farmer recall procedures are not affected by within-field variability, as farmers supply estimates on a whole plot basis. Variance in farmer recall data is therefore less likely than in crop-cut data. Still, both methods will result in a wide range of reported yield levels. For example, using crop cuts in countrywide surveys in Uganda and Tanzania, Nweke et al. (1998; 1999) reported cassava yields that ranged from 0.4 to 43.6 t/ha for Uganda and 1.5 to 35.0 t/ha for Tanzania. It should be noted that when such wide ranges in yields are obtained from farmer recall, some authors discard the data, as they question the reliability of farmer estimates (see, for example, Wortmann and Kaizzi 1998).

## Conclusion

The crop-cut and farmer-estimation methods both have their own inherent biases and difficulties. Detailed studies show that crop cuts gave 14 to 38 percent higher yield estimates than whole plot reference harvests, while farmer recall estimates overestimated yields by less than 15 percent. Other studies comparing crop cuts with farmer recall reported that crop-cut estimates gave 30 to 100 percent higher yield estimates than farmer estimates. Only in the case of very careful and detailed measurements in commercial agriculture (such as in Sweden and the United States) did crop cuts not overestimate yields.

Apart from its inherent upward bias due to measurement errors, the two most important problems associated with the crop-cut method include its high cost and time requirements and the need to use a clustered sampling strategy, which introduces an additional sampling error. The farmer estimation method generally results in farmer estimates that are closer to the objective reference level of yields determined by whole plot harvests than do crop-cut estimates. In addition, the method is fast and cheap and allows for a random sampling strategy and thus a lower level of sampling error. However, key problems with farmer estimates in the Ugandan context include the use of national average conversion units, rather than locally specific units, when converting nonstandard harvest units; poor data quality from lengthy interviews; and conscious over- or underreporting of crop production. These problems may result in large non-sampling errors (measurement and response errors) when survey design is poor and enumerators are not strictly supervised.

Both the crop-cut and the farmer-estimation methods have their own problems and advantages. Due to the lack of studies that have quantified sampling and non-sampling errors, no conclusive evidence exists that strongly favors one method above the other. Consequently national statistical institutes in countries such as Sweden, Rwanda, and Kenya prefer to use farmer recall data to obtain production estimates (pers. comm., G. Ländell, Statistics Sweden, 2010; Mpyisi 2002; Murphy, Casley, and Curry 1991), whereas others, including India, Zimbabwe, Niger and Benin, prefer to use the crop-cut method (MSPI 2008; Murphy, Casley, and Curry 1991). The US Department of Agriculture (USDA) uses a combination of farmer recall for their agricultural census and crop cuts for yield estimations of specific major crops in specific states. Several European countries prefer to use more expensive crop cuts for potatoes, while using cheaper methodologies such as farmer recall, expert assessment or purchase records for other crops (Bradbury 1996b). Murphy, Casley, and Curry (1991) also recommend using crop cuts for root crops. Uganda opted to use crop cuts in the annual crop yield surveys of 1967 and 1968 and in the agricultural census of 1990/91, but UBOS has been using farmer recall in the agricultural module of the two most recent national household surveys and in the most recent agricultural census. By doing so, Uganda seems to be following a worldwide trend whereby the historically preferred crop-cut method is slowly being replaced by the farmer recall method. Only a few countries, like Sweden, have based their decision on detailed studies within the framework of an agricultural census or national yield survey. It remains to be seen whether this trend will improve the quality—reduce total error—of crop yield estimations at the national level.

# 4. OTHER METHODS TO ESTIMATE CROP PRODUCTION

In Section 3, the two most common methods to estimate crop production for an individual plot, field, or farm–crop cuts and farmer estimates–were discussed. In this section, a range of other methods that are used to estimate crop production are described. These include daily recording, whole plot harvesting, sampling of harvest units, expert assessments, crop cards, crop modeling, purchase records, allometric models, and remote sensing.

## Daily Recording

Daily recording is the most intensive method for estimating crop production at the smallholder farmer level. It was used in the Ugandan agricultural census of 1965. At the start of the exercise, enumerators visit each plot of a farm household and record its surface area. Over a given time period, such as a cropping season or year, the enumerators will visit the farmers on a regular, frequent basis (ideally daily) to record the weight and *state of harvest* of any crop that has been harvested since the previous visit. From time to time, the enumerator may take subsamples of the harvested crops to determine factors for converting to a *standard state of harvest* for each crop.

Daily recording measures the economic yield. Due to its frequent recording, this method is able to capture multiple harvesting of the same plot, a common practice for crops with an extended harvest period, such as cassava, banana, or coffee, but also for crops with staggered ripening, such as green maize or indeterminate legumes. In addition, this method minimizes unrecorded "losses" due to eating or selling. As detailed area measurements of each plot are taken at the start of the exercise, crop yields can be calculated without an additional source of error. When enumerators do their job as requested and farmers do not harvest a specific crop from more than one field per day, this method may generate very high quality data.

However, the method is very labor-intensive and thus requires cluster sampling (Muwanga-Zake 1985), which has a negative impact on overall sampling error. The daily weighing and recording operations increase the likelihood of measurement and recording errors. Other disadvantages observed with this method include enumerators lacking motivation to visit each farmer every day and farmers mixing harvests from various plots in cases where they harvest the same crop from several plots in one day (Muwanga-Zake 1985).

When this method was used in the 1965 agricultural census, the published crop yield estimates per region were based, in some regions, on a very limited number of plots (a maximum of 235 plots, very often less than 100 plots, and in a few cases only 2 plots per crop per region). It was argued in the report on the census that the sampling error might be expected to be large, especially in those estimates that were obtained on the basis of a very limited amount of plots (MAC 1967). In addition, non-sampling errors may also have been high, partly due to possible errors in weighing or failure to weigh the entire harvested crop, but more importantly due to the use of average national conversion factors to convert the recorded weights into standard harvest conditions. Though the conversion factors that were used were calculated from data collected during the survey, it was realized that more work was required to estimate conversion factors with a high degree of accuracy.

## Whole Plot Harvest

Harvesting entire fields to determine crop yield is normally done during detailed farm surveys and in demonstration plots (Norman et al. 1995). Harvesting on-farm trials often also involves harvesting the whole plot, with the difference that one or more boundary lines are excluded as these may not reflect the tested treatment due to boundary effects. Before harvesting, plot boundaries should be clearly marked and the harvest area calculated. Crops that have a defined maturity date, such as cereals or legumes with a determinate growth habit, can be harvested in a single operation. Legumes with an indeterminate growth habit such as common bean, cowpea, and mung bean, or crops with staggered harvests throughout the season or year, such as banana or cassava, will require multiple harvests per plot. Each harvest is dried (if appropriate) and weighed separately. Individual harvest weights are summed up to obtain total production and to calculate crop yield.

Whole plot harvests measure the *harvested yield* (biological yield minus harvest losses in the field). The main advantage of this method is that it is almost bias-free, since all sources of upward bias reported for crop cuts can be eliminated when the entire field is harvested. As such, this method is regarded as the absolute standard for crop yield estimations, especially if done together with the farmer (Casley and Kumar 1988). Still, Murphy, Casley, and Curry (1991) point out that the required area measurement may likely introduce a limited source of downward bias. This is especially the case with irregular shaped plots, whereby enumerators will have to approximate curved lines with straight lines in order to calculate the surface area. It has been noted that enumerators tend to minimize the exclusion of planted areas, while forgetting to include non-planted areas. This may introduce an upward bias of up to 5 percent in the area estimation, which translates into a limited underestimation of the harvested yield.

Whole plot harvesting requires the enumerator to be present at the time of harvest. According to Poate (1988), farmers do not seem to find this intrusive and in many surveys farmers have cooperated willingly. They may benefit from the additional labor provided by the enumerator. The main downside of the method is related to the large volume of work involved. This makes it unsuitable for moderate-to-large sample sizes or multiple crop studies. It is, however, a good method for small-scale investigations of a case-study nature (Poate 1988). In this case, complete harvesting generates more accurate data than crop cuts because the bias from within-field variability, which commonly is 40–60 percent of total yield variability, is removed in whole plot harvesting. Where whole fields average less than 0.5 ha, complete harvesting takes a similar amount of time as crop cuts in two or three subplots per field (Casley and Kumar 1988).

### Sampling of Harvest Units

Instead of harvesting and weighing the whole field, the enumerator may wait for the farmer to harvest his or her field and estimate the number of the units (such as sacks, baskets, and bundles) harvested by the farmer. The enumerator then randomly selects a number of harvest units and weighs these to obtain an average unit weight. Ideally, sampling of harvest units is done just before storage and includes a measurement of the moisture content of the harvested product (Casley and Kumar 1988).

This method, the sampling of harvest units, measures either harvested yield or economic yield, depending on the time between harvesting and sampling (that is, the amount of postharvest losses). The technique is straightforward and can be used on larger samples than is possible with the crop-cut and whole-plot harvesting methods. Unlike farmer estimates, it does not matter if the harvest units are peculiar to each individual farmer, as the enumerator either weighs the complete harvest or weighs a random, unbiased, selection of harvest units of each farmer (Poate 1988). When the harvest is stored in one or several large granaries or stores, the enumerator will need a degree of analytical skill to accurately estimate total production (Rozelle 1991).

The following conditions have to be met to estimate crop production for a specific plot using the sampling of harvest units method (Casley and Kumar 1988):

- harvest must be collected in identifiable and complete units and reviewed before stored in a granary or otherwise disposed;
- units should not be too variable, so average unit weight can be estimated without too much error;
- crops should be harvested at once; and
- the enumerator should make the estimations shortly after harvesting.

In addition, the harvested units should all originate from one specific plot. This especially is a concern if a household has multiple plots with the same crop or one field with the crop of interest partially intercropped with a second crop. As the above conditions are usually not met, Poate and Casley (1985) find this method more appropriate to estimate crop production at the farm level than to estimate crop yield at the individual plot level. Rozelle (1991) points out that, where the enumerator was unable to visit the household directly after harvesting, this problem may be overcome by including questions to estimate the amounts of the harvest that have already been used. However, this method is considered unsuitable for crops with an extended harvest period, such as root crops, banana, and cotton.

### Expert Assessment

Extension staff or field technicians that have a lot of experience with a crop can estimate crop yields by either visually assessing the field or estimating yields on the basis of a combination of tools. This gives an estimation of biological yield. Extension staff or field technicians are often able to estimate crop production or yield by visually assessing the condition (color, plant vigor, plant density, and so on) of the crop in the field. This is known as *eye assessment*. In the 1990s, several European countries, including Germany, the Netherlands, Belgium and Ireland, used eye assessment to estimate crop yields for their annual agricultural statistics (Bradbury 1994).

In the United States and Australia, eye assessment has been upgraded through a combination of visual assessment, field measurements, and empirical formulas to a so-called *expert assessment* method. For cereals and grain legumes, the yield in t/ha is estimated by multiplying the average number of grains per head by the average number of heads per 5 m row and dividing this by a constant *K* that depends on the row spacing and grain weight. Counts should be carried out in at least 10 representative sites within a field (DPI 2010). For cotton, extension staff may count the number of cotton bolls that are open or expected to open by harvest in 10 representative one row-feet sections in the field. In each section, all bolls on three plants are picked and weighed to determine average boll weight. Assuming a certain picker efficiency and gin turnout and knowing the row spacing, the lint yield may be estimated (Goodman and Monks 2003). Expert assessment may become so detailed that the difference between this method and that of crop cuts on the basis of row segments may become blurred, though expert assessments will never involve harvesting the whole row segment.

The expert assessment method can be applied on a relatively large scale, compared with the crop-cut method, though on a smaller scale than farmer estimations. A second advantage of this method is that it does not require area estimations and does eliminate a source of potential bias. However, eye estimations of crop yield require not only practical but also technical familiarity with the yield potential of different varieties and their relative performance in different environments (David 1978). The accuracy of the yield assessment, therefore, will strongly depend on the level of expertise of the expert. An important advantage of the method is that one team of experts can be used throughout a study, which will result in a similar bias for all yield estimations (Rozelle 1991). When assessments are made by extension officers, yield estimations may be upward biased, especially if the assessments are made in their own work area and the information collected thus pertains to the quality of their own work (Casley and Kumar 1988). Bradbury (1996b), in contrast, reports that yield estimates by expert judgment in Europe are generally considered to be biased downward.

Few studies have compared expert assessments with other yield or production estimation methods and their results are contradicting. David (1978) observed a poor correlation of rice yields that were eye estimated by experts and actual crop yields and concluded that eye estimations of yield should not be used. However, Casley and Kumar (1988) observed in Zimbabwe that expert assessment was closely related (< 10 percent difference) to farmer estimates. Considering that a national survey or an agricultural census requires yield estimates of a large range of crops, it will be difficult to find experts that have the required practical and technical experience to provide accurate estimations across all crops.

## Crop Cards

The crop card method is a refined version of the farmer recall procedure. It also estimates economic yield. The crop card method was developed to obtain more reliable harvest estimates for crops with an extended harvest period, such as cassava, banana, and sweet potato, as farmers may have problems in accurately remembering the amounts they harvested over time from one or several plots. Each farmer in the survey or census is given a set of crop cards by a crop card monitor (CCM) and receives training on how to use them. After each harvest operation, farmers are required to record the quantity they harvested in local harvesting units. The CCM is expected to visit each farmer on a regular basis to monitor the recordings of the farmer and correct any problems. After a certain period, the CCM collects all cards for processing.

The method was tested in Uganda during the UNHS of 2005/06 and compared with farmer-recall estimates. Ssekiboobo (2007) reports several problems that include irregular monitoring by enumerators; illiterate farmers who were not able to fill in the crop cards; some recordings that also included crop purchases; and a very large range of observed harvest units. The first three problems resulted in 23 percent of the records being incomplete or faulty (Sempungu 2010). Some of these problems may be overcome by providing households with a standard size bucket or other container to record harvests and a crop card that contains numerous drawings of the bucket on which farmers can cross out the appropriate number of buckets for each harvest (de Jaegher 1988).

Using data collected for the testing of the crop card method for the UNHS 2005/06, Carletto et al. (2010) showed that crop card production estimates were 40 to 60 percent lower than farmer recall production estimates for both crops with an extended harvest time (cassava and banana) and for other crops (maize and beans). This is in line with findings from Sempungu (2010), who, using the same data set, found that cassava and sweet potato yield estimates from the crop card method were, respectively, 30 and 46 percent lower than those obtained from farmer recall.[2] The above studies suggest, first, that farmers were either seriously overestimating crop production during the recall exercise or underestimating crop production with the crop card method and, second, the upward or downward bias that resulted does not seem to depend on the type of crop. This is contradictory to the assumption that farmers have difficulties in accurately recalling multiple harvests of crops over an extended harvest period.

## Crop Modeling

Crop modeling is widely used to estimate average biological yields in the conditions of smallholder farmers. Crop models vary widely in their complexity. The simplest set of models has an empirical-statistical nature, whereas the most complex models are based on crop physiology. Empirical-statistical models aim to find the best correlation between crop yield and environmental factors (often rainfall) from long-term data sets. The established relations are then used to predict crop yield at a regional or national level on the basis of actual environmental observations. Crop growth models estimate crop yield as a function of physiological processes and environmental conditions. They range from relatively simple models taking into account only basic crop physiology processes (for example, Penman-Monteith models based on estimations of actual evapotranspiration) to extremely complex models that estimate daily gains in biomass production by taking into account all known interactions between the environment and physiological processes (Sawasawa 2003).

Crop models can be used to predict crop yields in specific conditions or a range of conditions and are an extremely useful tool in research studies exploring the impact of specific factors on average crop yield. They cannot be used, however, to predict crop yields for individual farmer fields, as this requires far too many input data.

[2] Sempungu (2010) reports that the average cassava yield obtained through farmer recall was 363 kg of fresh cassava per acre. This translates into 0.9 t/ha of fresh cassava, an estimate that is far below the average fresh cassava yields of 8.3 to 11.7 t/ha obtained through a farmer recall procedure in Uganda (Fermont et al. 2009).

## Other Methods

### *Purchase Records from Agro-industries*

In the case of pure cash crops, such as coffee, cotton, tea, cocoa, and sugarcane, purchase records for individual farmers can be obtained from agro-industries and linked to farmers in the agricultural survey. Purchase records can be a valuable source of production estimates (economic yield) at regional or national levels. Where all production is sold to agro-industries and their records can be linked to individual farmers in the survey, production estimates at the farm level can be obtained. These may be converted to crop yields if total crop area is known as well. In developed countries, this works well. For example, Sweden and Norway obtain records on sugar beet production from the agro-industry and the national grain administrator, respectively (Bradbury 1996a). In Uganda, this may work for cotton, though linking records from the cotton ginneries to individual farmers in the agricultural survey may not be straightforward. Still, data on total cotton production from each ginnery and aggregated data on cotton area in the same region can be used to obtain a proxy estimation of cotton yield in a region. For coffee, this may be more difficult, as coffee is sold in several batches to one or more buyers, and some of it is consumed locally.

### *Allometric Models*

Allometric models are mathematical relationships between plant morphological attributes and crop yield. When these relationships are sufficiently accurate ($R^2$ greater than 0.75), nondestructive measurements of several morphological characteristics on a selected number of plants can be used to predict biological yield in a field. Allometric models should be based on variables that can be quantified easily using rapid, inexpensive, and nondestructive methods of data collection. For bananas in Uganda, Wairegi et al. (2009) find that a multivariate model using girth of the pseudostem at base and at 1 m, the number of hands, and the number of fingers gave a robust prediction of bunch weight. Tittonell et al. (2005) used plant height and ear length to predict maize yields in western Kenya. Both models were valid for a range of cultivars and soil fertility levels, whereas the banana model was also valid for a range of agroecologies and not specific to development stage. This is an indication that such models can be used in a wide range of conditions. Labor demands for data collection for use in allometric models are likely to be somewhat lower than for crop cuts, but enumerators will require additional training and an adapted datasheet for data collection (pers. comm., L. Wairegi, 2010).

### *Remote Sensing*

Crop yield is the result of a complex of environmental factors (such as soil, weather, pest and disease outbreaks) and farmer management. The total effect of these factors translates into the production of green biomass and finally yield. Green plants have a unique spectral reflectance or spectral signature. The proportion of radiation reflected in different parts of the spectrum depends on the state, structure, and composition of the plant. This information is captured in satellite images as spectral data (that is, spectral reflection in various bands), which can be used to construct several vegetation indexes such as the normalized difference vegetation index (NDVI). High correlations are found between the NDVI and green biomass in studies done at field level (Groten 1993). To correlate NDVI values to crop types and crop yield requires ground truthing in the form of field visits to determine crop types and actual yield estimations in selected fields (pixels) that cover the full range of observed NDVI values.

Use of remote sensing to estimate *biological crop yields* is being explored in many countries such as the United States, China, and India, and likely will become the keystone of agricultural statistics in the future (Zhao, Shi, and Wei 2007). However, considerable research is still needed before remote sensing can be widely applied to estimate crop yields. In India, for example, vegetation indexes from satellite images show only a moderate correlation ($R^2$ between 0.45 and 0.54) with crop-cut data (Singh 2003). One important limitation for the use of satellite images to estimate crop yields of smallholder farmers is that the resolution of available satellite imagery—the pixel size—is not sufficiently detailed to capture the variability of crops and crop performance in smallholder fields that often are less than 0.1 ha in size and may be intercropped as well. A detailed field level study by Sawasawa (2003) on rice in India highlights this problem by showing that, even with high resolution images, only 52 percent of observed yield variability is captured. Other problems that limit the current usefulness of remote sensing for developing countries include cloud coverage, the need for expensive ground truthing, the need for specialist knowledge, and the need of expensive image processing software (Reynolds et al. 2000).

# 5. ESTIMATING CROP AREA

To convert crop production to crop yield estimates, production estimates are divided by area estimates. To minimize the error introduced by dividing the production estimates by area estimates, area measurements should have a high degree of accuracy (Diskin 1997). The choice of the most appropriate measurement technique to estimate crop area will depend on the objectives of the project and various operational factors, such as land configuration, field shape, crop type, cropping pattern, available skills, and resources (Casley and Kumar 1988). Crop area may be estimated either directly by measurements or by visual estimation. Five methods to measure crop area are described here and their advantages and disadvantages discussed. The final subsection focuses on farmer estimations of crop area. It should be kept in mind that any method that directly measures crop area depends on the farmer supplying information on his or her plots to the enumerator. In this context, Belshaw (1982) observed that the 1965 agricultural census underestimated crop area in Uganda, as farmers did not disclose the existence of all distant plots to the enumerators for fear of increased tax assessment.

## Polygon Method

The traditional method to measure crop area is the polygon method, also known as traverse measurement, traversing, chain and compass, or the Topofil method (MAC 1965; de Groote and Traoré 2005; Schøning et al. 2005). In the case of a plot with straight sides, the method involves measuring the length of each side and the angle of each corner using a Trumeter wheel or a measuring tape and a compass. The surface area of the plot can then be calculated using trigonometry (FAO 1982; Casley and Kumar 1988). Using a measuring tape and compass, this method was used in the 1990/91 agricultural census in Uganda (Menyha 2008). Where the plot has an irregular shape or curvilinear boundaries, the enumerator can transform the area into an approximate polygon with straight sides by demarcating its vertexes on the ground. A so-called give and take process should be followed, whereby the enumerator takes care to balance the protruding pieces left out in the process by including other small pieces that are not part of the plot (Casley and Kumar 1988). During the give and take process and during the measurement process, errors are introduced. Where the polygon does not close and the closing error is larger than 3 percent of the perimeter of the polygon, the measurement procedure should be repeated (Casley and Kumar 1988).

The polygon method is commonly considered the most objective method to accurately estimate crop areas and may thus, according to Diskin (1997), be worth the extra time, training, and cost.

## Rectangulation and Triangulation

A second method of measuring crop area is the rectangulation and triangulation method. Enumerators split the plot or field into a number of (imaginary) rectangles and triangles and measure the length and width of each rectangle and the height and base of each triangle using either a Trumeter wheel or a measuring tape. The total area of the plot is found by adding up the areas of the individual rectangles and triangles.

In a 1963 pilot study for the 1965 agricultural census in Uganda, the rectangulation and triangulation method was compared to the polygon method (MAC 1965). The latter was assumed to give the most accurate area. The polygon method took twice as much time and required two enumerators instead of one enumerator for the rectangulation and triangulation method. (However, Muwanga-Zake (1985) argues that to properly measure triangles in the field, two enumerators are required.) In this pilot study, the rectangulation and triangulation method underestimated the total cultivated area and area per holding by approximately 5 percent, whereas some individual crop areas were underestimated by 12–15 percent. However, because the rectangulation method tended to overestimate crop areas in the 1959 "Investigation into Acreage Statistics," Volume I of the report on the 1965 Uganda Census of Agriculture concluded that "this, one may hope, may mean that there is no major bias in the method, the bias being in individual enumerators" (MAC 1965). As individual enumerator error may be in either direction, aggregating their results will tend toward mutual cancellation. However, Muwanga-Zake (1985) points out that enumerator bias may be substantial in districts that are covered by only a few enumerators. Other problems with the rectangulation and triangulation method include the necessity for enumerators to walk through the fields to take measurements, with the possibility of trampling crops, and the difficulty of visualizing rectangles and triangles in irregular fields or fields with high-growing crops (Muwanga-Zake 1985).

### $P^2/A$ Method

The Rwandan National Institute of Statistics uses a pacing method to compute crop areas. The $P^2/A$ method, whereby $P$ stands for perimeter and $A$ for area, is based on the relative stable relation between the perimeter of a field and its area. The ratio between $P^2$ and $A$ depends on the plot shape and ranges from 16 for a plot with equal sides to 29 for a plot with a 1:5 ratio between length and width. The enumerator paces the field and records the number of steps taken. To reduce error, the length of the enumerator's steps is calibrated in a range of fields with varying slope (Mpyisi 2002).

The $P^2/A$ method is much faster than the polygon and the rectangulation and triangulation methods, it has lower costs and less supervision requirements. In addition, it can be used on irregularly shaped plots. A study in Rwanda showed that, with a net error as low as 2 percent, compared with the polygon method, the results of the $P^2/A$ method were considered accurate (Mpyisi 2002). It concluded that the method produces unbiased estimates of crop areas and is especially useful in regional or national surveys.

### Global Positioning System (GPS)

A GPS device determines continuously the longitude and latitude of its position on earth using at least three satellites in the GPS network of satellites. Holding a GPS device, the enumerator decides on a starting point at one corner of the field and walks the whole perimeter of the field. All data are stored in a track-log on the GPS, which can be used to calculate the area of the field. Most GPS models will allow for direct area calculation.

The Uganda Bureau of Statistics has been involved in testing the accuracy of GPS estimates for crop area (Schøning et al. 2005). During the 2003 Pilot Census of Agriculture, GPS area estimates were compared to area estimates obtained with the polygon method. The main observed advantage of the GPS method was time saving: the GPS equipment resulted in an overall time saving of more than 300 percent. On average, GPS area estimates were 6–12 percent lower than area estimates from the polygon method. Analyzing the results by plot size shows that GPS estimates were strongly correlated ($R^2 = 0.90$) with the polygon estimates for large plots (greater than 0.5 ha). However, for small plots (less than 0.5 ha) the correlation was very poor ($R^2 = 0.12$), with GPS area estimates being significantly smaller than area estimates from the polygon method.

The accuracy of any GPS receiver is around ± 15 m. For small plots, this may translate into large errors in the estimation of area. Imagine a plot measuring 30 x 33.3 m (0.1 ha): in the worst case scenario, a GPS receiver might record this as a plot of 60 x 63.3 m, overestimating the plot area by 385 percent, or as 0 x 3.3 m, resulting in a plot area of 0 $m^2$. The accuracy of a GPS receiver may be improved by installing a second GPS receiver in a location with known coordinates–a Differential Global Positioning System. For any given time, the accuracy error is known for the second receiver and can be used to correct the coordinates recorded by the first receiver.

Other reported problems observed when using GPS systems include erroneous readings due to interference of trees and projection problems in hilly areas (Schøning et al. 2005; Sempungu 2010). It should be noted, however, that the latter is a problem for any method measuring crop area on steep slopes.

This is related to the fact that the measured crop area should not be the physical area measured on the ground, but its projection onto a horizontal plane (Muwanga-Zake 1985). The projection problem is especially important on steep slopes greater than 10 degrees. As the introduced error is 0.4 and 1.5 percent for slopes of 5 and 10 degrees, respectively, the projection problem may be ignored on slopes of less than 10 degrees.

### Remote Sensing

Three common problems for all methods that involve direct area measurements in the field are unclear boundaries, the wide scattering of plots, and difficult terrain. This may make direct area measurement by enumerators extremely time consuming, and thus unfeasible in some cases (Diskin 1997). In addition, Ssekiboobo (2007) notes that in Uganda some respondents refuse to have their plots measured and that direct area measurements are not possible in regions with security problems. In such conditions, one will need to revert to using farmer estimates. In the future, however, remote sensing may become an option. Currently this method is still facing too many problems to be used in Uganda, where agricultural production is dominated by small plots, diverse planting dates, dispersed trees and intercropping systems. Even in the United States, where agriculture is dominated by monocropping on large fields, the use of remote sensing techniques is still limited to enhancing area estimates obtained using other methods in a few selected states.

### Farmer Assessment of Crop Area

During interviews, farmers may be asked to estimate either the surface area of their various plots or of the total farm. Alternatively, the enumerator and the farmer may visit all plots of a household and estimate the surface area visually (David 1978). In Uganda, the agricultural module of the population census of 2002 used farmer estimates to obtain area estimations (Menyha 2008).

De Groote and Traoré (2005) mention the following problems with the use of farmer area estimations:

- Farmers may be suspicious of enumerators because they fear taxes.
- In areas where land markets are just emerging, there will probably not have been a need for area units until recently. Therefore, precise local measurement units may not have been developed yet or they may vary between regions, villages, and even farmers.
- Farmers have little access to formal agricultural education and thus lack measurement techniques and quantitative skills.
- Data quality is greatly affected by the size of the unit (such as $m^2$ versus ha) and the resulting rounding error. The use of acres or hectares may introduce a considerable error. David (1978) found that farmers are likely to round off figures to the nearest quarter or third of an acre.

Due to the multitude of possible problems, FAO (1982) considers the accuracy of farmer surface area estimations to be insufficient. However, various studies have shown that farmers can give rather accurate estimates of crop areas. David (1978) concluded from two studies in the Philippines that farmers overestimated area by just 6 to 8 percent, while in a third study farmers slightly underestimated area. Correlations between measured and estimated areas were high ($R^2$ between 0.7 and 0.9) in all studies. Swedish farmers overestimated crop areas by only 3 to 4 percent (Statistics Sweden 1998). The statisticians involved with this Swedish study suggested that the overestimation may have been due to differences in definition, with farmers including turn-lands, field roads, and ditches in their estimation, while Statistics Sweden did not. Because farmers in China and Indonesia easily could provide accurate estimates of cultivated land, but Malawian farmers could not, Rozelle (1991) concludes that where land is less scarce, it is more difficult to obtain accurate area estimations. Verma et al. (1988) argue that the quality of the surface area estimations depends on how familiar farmers are with the concept on units of area and thus varies strongly between countries.

Ajayi and Waibel (2000) observed in Ivory Coast that farmers are able to confidently estimate crop areas when plot size is larger than the local area unit (± 0.25 ha), but when plot size is smaller than the local area unit farmers greatly overestimate plot size (125 percent error). This is in line with findings from a large study in Mali by de Groote and Traoré (2005), who also found that farmers overestimated small plots of less than 1 ha. However, the error was much smaller than in the Ajayi and Waibel study, possibly because enumerators discussed the estimates with the farmers in the field. De Groote and Traoré (2005) also showed that the error in area estimation varies between crops, with farmers being able to supply more accurate estimates (8 percent error) for cotton fields, which were measured in the past by the cotton company, and less accurate estimates (14 percent error) for cereal fields. Several authors (David 1978; Ajayi and Waibel 2000; de Groote and Traoré 2005) observed that the accuracy of farmer estimates reduces with increasing plot size, resulting in underestimations if plot size is larger than a few hectares.

Two strategies can be employed to increase the accuracy of farmer area estimates. First, one or more subsamples of the sample population can be defined from whom enumerators obtain both farmer estimates and direct area measurements and a correction factor is defined on the basis of their correlation (David 1978). Considering the observed overestimation of plots smaller than the local area unit and underestimation of large plots, this strategy will be specifically useful in areas with relatively small and large plots (less than 1 acre or greater than 2 hectares in the Ugandan context). A second strategy is to allow the enumerator to discuss the area estimates with the farmer when in the field. Pointing out inconsistencies to the farmer will improve the accuracy of the estimation (de Groote and Traoré 2005).

# 6. ERRORS AND BIASES

The total error in crop yield estimates is a combination of sampling and non-sampling error. Sampling error is the error associated with the selection of a sample population rather than using the whole population. Where a census covers the entire farming population, there is no sampling error. Non-sampling errors arise from data collection and data entry procedures and include incorrect sample listing, response errors and biases, measurement errors and biases, incorrect form filling, and errors made while transferring, entering, and processing data (Carfagna 2007; Poate 1988). Errors are random deviations from the actual value, while biases are consistent over- or underestimations of the actual value. The choice of method to estimate crop production, crop area, and ultimately crop yield may influence the sampling error, as the choice of method has implications for the sampling strategy that is required and the non-sampling errors due to method-specific susceptibility to specific response and measurement errors.

## Sampling Error in Relation to Sampling Strategies

Sampling error varies with the square root of the sample size: thus quadrupling the sample size halves the sampling error. National agricultural surveys that use sufficiently large population samples drawn at random from the total population will keep the sampling error within acceptable limits. The 1965 Agricultural Census in Uganda was carried out on a 1 percent sample of the total number of agricultural holders. At the national level, this resulted in a sampling error of approximately 1 percent for area estimates, but sampling error rose to between 2 and 7 percent at the district level for most crop areas. Taking into account that non-sampling errors were not quantified, it is argued that the sample size should have been 2 percent for sufficiently small confidence intervals around the estimates obtained (Muwanga-Zake 1985).

Agricultural censuses and surveys in Uganda commonly use a two-stage stratified design, whereby a simple random sampling is used to select enumeration areas at the first stage and farm holders at the second (Muwanga-Zake 1985). The two-stage stratification design results in a clustering of holders within the enumeration areas. Considering that holders within an enumeration area are likely to be more similar to each other than they are to holders from different enumeration areas, this sampling design inherently has a higher sampling error than complete random sampling of holders at the national level. However, from a practical point of view, such a completely randomized sampling scheme would be a logistical nightmare in survey implementation.

Methods that involve close supervision from the enumerator (such as crop cuts, whole plot harvesting, sampling harvest units, or crop cards) cannot be applied to every individual within the sample. Due to budgetary limitations they will be restricted to a subsample of the total sample population. These logistical limitations require that a cluster sampling strategy is used to select the subsample. Due to lower sample numbers and cluster sampling, supervision-intense methods will inherently have a lower level of sample precision and a higher sampling error than methods that require less intensive supervision, such as farmer recall. Considering that Uganda has moved from very intense yield estimation methods to less intense methods (daily recording in 1965; crop cuts in 1967, 1968, and 1990; with farmer recall since 1995), it can be expected that the sampling error associated with yield estimations has decreased over time. Unfortunately, sampling errors for yield estimations, as in so many other countries, have never been quantified in any of the agricultural surveys or censuses in Uganda.

## Non-sampling Errors

Non-sampling errors are always present and generally can be expected to increase as the number of respondents and the complexity of the questions increase. They contribute much more than sampling error to the total means squared error (MSE), which is often used as a quality measure of estimators (Carfagna 2007).

The most common non-sampling errors include measurement and response errors or bias. Measurement error can be defined as the difference between the actual value and the measured value. It consists of random errors (a reading error on a weighing scale, for example), which can be reduced by repeating the measurement more times, and systematic errors or bias (such as incorrect calibration of a weighing scale), which require adjustment of the inaccuracy in the measurement method (perhaps by using a different weighing scale). Response errors and biases are those errors and biases associated with respondents supplying, knowingly or unknowingly, wrong information (such as under- or over-reporting of production).

Farmer estimations and the crop-card method experience both response and measurement error or bias, while the crop-cut method is dominated by measurement error or bias. Area estimation methods, such as the $P^2/A$ or the GPS, are also dominated by measurement errors but normally do not have a bias (such as consistent over- or underestimation of true mean). Whole plot harvesting and the polygon area estimation method are considered to have the least non-sampling errors.

Response and measurement errors or biases are a major source of error in survey estimates, but, like other non-sampling errors, they are hard to measure and rarely quantified (Kalton 2005). Casley and Kumar (1988) are one of the few who have quantified measurement error in a crop-cut exercise. From the 20 percent upward bias they report for crop cuts in comparison to whole plot harvesting, 15 percent was due to measurement errors and 5 percent to postharvest losses. Considering that their study was carried out with great precision, they conclude that measurement bias in less-well-controlled studies must be much larger than 15 percent. Poate (1988), who estimated total bias for crop cuts to be about 10 percent and those for farmer recall about 15 percent, seems to make conservative estimate. The large number of possible error or bias sources mentioned in Section 3 also indicates that total bias or error for crop cuts and farmer recall may be much larger than 15 percent.

### Conversion Units and Non-sampling Error

Crop yields are expressed either as dry matter (cereals, legumes, and oil seeds) or as fresh matter (banana, cassava, sweet potato, Irish potato, among others). For any crop and any method, care should be taken that all observations throughout a survey or census are made for the same state of harvest (for maize, for example, either recorded as grain on the cob or as shelled grain and not for a mixture of the two (Poate 1988). For proper comparison across fields, farms, and regions, all harvest estimates should be standardized to a common base, that is, constant moisture content, standard weight unit, and common state of harvest. This will require the use of one or more conversion factors that may include local unit weight conversion factors, postharvest conversion factors (threshing, shelling, or drying), and moisture content conversion factors. Such conversion factors are a possible large source of non-sampling error.

Both the type and size of local harvest units may vary widely between regions, villages, and even farmers (Diskin 1997). Ssekiboobo (2007) observed that this is also the case in Uganda. A Nigerian study demonstrated that variation in weight may be as high as 100 percent between regions and up to 70 percent within regions (Casley and Kumar 1988). The use of national conversion factors for local weights therefore will introduce a large source of non-sampling error into production or yield estimates. The only way to reduce this error source is by determining local weight conversion factors at a lower level (such as district or county). Though this process may be somewhat labor-intensive, it will reduce the non-sampling error significantly, if carried out correctly.

Threshing, shelling, or peeling percentages and moisture content of harvest products vary much less widely than the weight of local harvest units (see, for example Fermont 2009). Mortensson et al. (2004) even argue that the impact of moisture content is of marginal importance, compared with other sources of error. It can thus be justified to use national conversion factors for threshing, shelling, or peeling percentage and moisture content. However, one should keep in mind that postharvest conversion units are based on specific crop conditions (millet in the head with a certain length of stalk attached, for example). These may not cover all crops and conditions that are found in the field, as Muwanga-Zake (1985) points out for the 1965 Ugandan agricultural census. To ensure that all harvest conditions and crops are covered, postharvest conversion factors can be determined on a limited amount of subsamples from various regions during the testing phase of the census.

In relation to conversion units, there are several general issues that require attention. When recording harvest data, enumerators may struggle with concepts that seem easy at a first glance, ”dry” harvest product, stalk length, and marketable cassava tubers are a few examples of concepts that seem objective but may be interpreted rather differently by various enumerators (Muwanga-Zake 1985). How dry is dry? Where should a banana stalk be cut when measuring a bunch? What size of cassava tuber is still marketable? Such details should be clearly spelled out in any survey and training sessions for enumerators. A second issue is related to enumerators handling large amounts of samples to determine conversion factors. If the handling load is too large, the transporting, threshing, peeling, or shelling, drying, and storing of such large numbers of samples may become difficult for many enumerators. The consequent risk of confusing samples if not properly labeled and handled may result in even higher non-sampling errors than the use of standard conversion factors. Thus, though the determination of conversion factors at district or parish levels will normally reduce non-sampling errors, overloading enumerators with too much work will result in the opposite.

# 7. GENERAL COMPLICATIONS IN ESTIMATING CROP AREA AND CROP YIELD IN SMALLHOLDER AGRICULTURE

Whatever methods are used to estimate crop area or crop yield in a specific area, accurate estimates in smallholder agriculture may be complicated by (1) heterogeneous crop performance, (2) continuous planting, (3) mixed cropping, (4) staggered harvesting for crops with an extended harvest period, and (5) planted area not being equal to the harvested area. These complications are discussed in detail in the subsections below. Two other issues that influence data quality and interpretation are the level at which data are aggregated and the variation of crop yield over time. These are discussed at the end of this section.

## Heterogeneous Crop Performance

Crop performance in any smallholder farming system is highly heterogeneous, both within and between plots, enumeration areas, and broader regions. Consequently, variance in any series of yield estimations will be high. Heterogeneity at plot level may be related to, among others, the presence of intercrops, trees, stumps, or anthills; local variability in soil characteristics; and non-uniform farm management. Within plot variation is commonly as high as 40 to 60 percent (Casley and Kumar 1988). Methods that estimate production based on subplots in a plot (crop cut and allometric models) will thus inherently have a larger variance than production estimates that are based on a whole plot observation. The reliability of the production or yield estimates can be improved by increasing the number of subplots sampled.

## Continuous Planting

Due to the relatively even distribution of rainfall in large parts of Uganda, farmers may plant and harvest crops throughout the year. This may seriously complicate the estimation of crop area and production. In an attempt to capture continuous cropping patterns, the 1965 agricultural census recorded crop areas for each sample holder at three times during the census year. However, it was noted that the holders changed the constituency of crops within a plot and plot boundaries so frequently that it was difficult to link the records of the various visits (MAC 1967). Subsequent Ugandan surveys, therefore, used a single visit to measure crop areas. However, they did not account for continuous planting, and Muwanga-Zake (1985) consequently concluded that a procedural bias exists in the estimation of crop areas in Uganda. This bias may be reduced by taking into account the period that each crop remains in the ground, which requires collection of planting and harvesting data for each stratum.

## Intercropping or Mixed Cropping

African farmers intercrop or relay crop their fields in order to spread risks, diversify their production, and increase total output of individual fields. In Uganda, crop areas have been recorded as pure or mixed stands for all crops. The 1965 agricultural census distinguished between crops that are the predominant and non-predominant crop in the mixture. Results showed that 70 to 80 percent of beans and maize and roughly 40 to 50 percent of sorghum, millet, groundnuts, and cassava were intercropped (MAC 1966). Figures from the 1990/91 census indicate that, with 80 to 90 percent of their area being in mixed stands, intercropping may have become more important for maize, beans, millet and groundnuts, whereas intercropping of cassava remained at 50 percent (MAAIF 1992). The effect of intercropping on the production and yield of individual crops is mostly negative, though in some cases intercropping may actually increase crop yields. The final impact on crop yield is the result of complex interactions of many factors that include relative time of planting, plant density, rainfall, soil fertility, and crop management, among others. Estimating the impact of intercropping on crop yields presents difficulties for any of the crop yield estimation methods discussed in this paper.

### Strategies to Handle Intercropping in Agricultural Statistics

Four strategies are commonly used to estimate crop area, production, and yields in farming systems that have an important proportion of crops produced under intercropping (Kelly et al. 1995). Each strategy has consequences for the accuracy of the resultant estimates.

#### *Strategy 1–Ignore Intercropping*

The first strategy completely ignores intercropped plots. Crop areas are recorded for sole cropped plots only, and the estimated total crop area is thus an underrepresentation of the actual area. The resultant average crop yields are thus an overestimation of actual crop yields. Total production for crop A is estimated as

$$\text{Total production crop A} = \sum \text{Area crop } A_{pure} \text{ x Avg. yield crop } A_{pure.} \qquad (2)$$

Depending on the importance of intercropping, this strategy may result in very important underestimation of total production for crop A.

#### *Strategy 2–Only Record Main Crop*

In the second strategy, intercropped plots are not ignored. However, only the main or predominant crop is recorded. Any minor crop is thus ignored. Estimates of crop area and crop yield are presented as if they were obtained in sole cropped plots, though in reality they were obtained from a mixture of pure and mixed stands. Total area for crop A is estimated as the sum of the total pure area of crop A and the total area in which crop A is the main crop. As areas with crop A as a minor crop are ignored, estimated crop area is still an underrepresentation of the actual area, though the underrepresentation will be significantly less than for strategy 1. Average yield is determined from a random selection of fields that have crop A either as a pure stand or as the main intercrop. Depending on how often a crop is grown as a minor crop, estimated crop yields are somewhat lower than actual crop yields. Total production for crop A is estimated as

$$\text{Total production crop A} = \sum \text{Area crop } A_{pure\ /\ main\ crop} \text{ x Avg. yield crop } A_{pure\ /\ main\ crop}. \qquad (3)$$

The estimation of total production according to this strategy may be quite realistic when (1) the average yield for crop A is estimated from a sufficiently large number of plots to capture the relative importance of pure stand and the various mixtures in which crop A is the predominant crop; and (2) crop A is not grown as a minor crop in prevalent intercropping mixtures.

#### *Strategy 3–Use Whole Plot as a Denominator For Each Crop in the Mixture*

In strategy 3, the entire plot size is used as a denominator for each crop in a mixture during both area and yield estimations. The crop mixture is indicated for each area and yield estimation. Total area for crop A consists of the total area for crop A as a pure stand plus total areas for crop A in all its recorded mixtures. If crop A is a minor crop in prevalent mixtures, total area for crop A will be overestimated. Average yield for crop A is determined separately for crop A as a pure stand and for each of its recorded mixtures. When average crop yields are presented by intercropping status, yield estimates may be close to actual yields.

To capture total production for crop A would involve inclusion of the areas and average yields of crop A for all recorded mixtures. Following Kelly et al. (1995), it is suggested here that the included mixtures be limited to the two most important mixtures for crop A within a region. Alternatively, a threshold (for example, area of mixture $x > 10$ percent of total area of crop A) may be used to decide whether or not to include a certain mixture in the estimations. Total production for crop A is then estimated as

$$\text{Total production crop A} = \sum \text{Area crop } A_{pure} \text{ x Avg. yield crop } A_{pure} + \sum \text{Area crop } A_{mix\_1} \text{ x Avg. yield crop } A_{mix\_1} + \sum \text{Area crop } A_{mix\_2} \text{ x Avg. yield crop } A_{mix\_2}, \quad (4)$$

where *mix_1* and *mix_2* represent the most common crop mixture for crop A. These may be mixtures in which crop A is the predominant crop or the minor crop. In those situations where the excluded mixtures represent relatively important areas, their exclusion will result in an underreporting of the total production of crop A. To reduce such underreporting, grouping of similar intercrops (such as sorghum and millet) of crop A may be done if it is judged that the impact of these intercrops on the yield of crop A will be similar.

### *Strategy 4–Allocate Part of Plot Size to Each Crop in the Mixture*

In strategy 4, the plot size is proportionally divided between the crops planted in the mixture during both area and yield estimations in order to "adjust" the observed area and yield estimations to pure stand estimations. The division of the area between the various crops can be done in three different ways:

*Strategy 4a*–visual estimation of the proportion occupied by each crop;

*Strategy 4b*–examining the seeding rates or measurements of crop density; or

*Strategy 4c*–using fixed area ratios for each intercrop combination.

Imagine a plot of 0.5 ha that is intercropped with maize and groundnuts, whereby maize takes up 30 percent and groundnuts take up 70 percent of the plot area, and 200 kg of maize and 250 kg of groundnuts were harvested from the whole plot. The adjusted areas for maize and groundnuts are 0.15 ha (0.5X 0.3) and 0.35 ha (0.5 X 0.7), respectively, whereas the adjusted crop yields for maize and groundnuts are 1.33 t/ha (0.2/0.15) and 0.71 t/ha (0.25/0.35), respectively. Total area for crop A is estimated as the sum of the adjusted crop areas, whereas average adjusted yield is determined from a random selection of plots that have crop A either as a pure stand or as a major or minor intercrop. Total production for crop A is then estimated as

$$\text{Total production crop A} = \sum \text{Area crop } A_{\text{adjusted to pure stand}} \text{ x Avg. yield crop } A_{\text{adjusted to pure stand}} \quad (5)$$

The estimation of total production of crop A will be quite close to its actual production unless the average yield of crop A in intercropped plots is much lower (> 50 percent) than that of crop A in pure stand.

### *Discussion of the Strategies*

Strategies 3 and 4 are the most commonly used around the world. FAO and some European countries use strategy 3 (Kelly et al. 1995; Mortensson, Landell, and Wahlstedt 2004), whereas all European countries reporting to Eurostat use strategy 4a (Mortensson, Landell, and Wahlstedt 2004). Strategy 4b is used in Rwanda (Kelly et al. 1995), while strategy 4c is used by many states in India (MSPI 2008).

Strategy 3, which uses the entire plot size as the denominator, allows for comparison of sole versus intercropped yields in cases where yields are reported together with the crop mixture they were obtained from. One important disadvantage of strategy 3 is that crop areas cannot be aggregated at farm or higher levels, since intercropped fields would be double counted. Strategy 4, which proportionally allocates area to each intercrop, attempts to remove the impact of intercropping on areas and yields as it adjusts all areas and yields to pure stand data. This facilitates comparison across regions or countries and removes the risk of double counting areas, but the reported crop yields do not show the impact of intercropping on those yields. Estimating area proportions (strategy 4a) may be a dubious or difficult exercise, especially if crops are planted at random or more than two crops are present in the plot. Using a fixed area ratio (strategy 4c) simplifies data collection by the enumerators and, although it will not result in correct estimations of crop yield at the individual plot level, it may generate acceptable results at higher aggregate levels (MSPI 2008).

In cases of intercropping systems with three or more crops, Kelly et al. (1995) suggest that only the two principal crops be reported in order to capture most of the production value, simplifying data recording and reducing possible recording errors. Considering that crop yields in intercropping systems may vary more widely than crop yields in pure stands, as they are affected by a larger range of variables, a larger number of observations will be required to obtain yield estimates with an acceptable confidence interval for intercropped fields than for pure stands.

Relay cropping and the mixing of annual with seasonal crops complicates the situation. Consider the following case: a field is planted with maize at the start of the first rainy season. A few weeks later, the farmer adds cassava to half of the field. During the second rainy season, he intercrops half of the cassava with beans and plants a second crop of cassava where the maize used to be. Estimation of crop areas and yields for the various crops will depend on the time of the field visit or recall time. In addition, farmers will commonly harvest each crop as a single entity; not noting what part of the harvest originates from which intercropping mix. Unless the enumerator is present at the harvest to record whether, for example, the maize harvest originates from a sole cropped maize plot or from a maize-cassava intercrop plot, it will be impossible to distinguish maize production from the two plots: therefore, maize yield can only be calculated as an average figure for the whole farm. Sequential cropping or growing cycles that exceed a single season or calendar year complicate the estimation of crop production and crop yield further. No simple solution is available for such situations.

In summary, African smallholder farmers commonly intercrop their fields. In Uganda, data from the 1990/91 agricultural census indicate that this may be as high as 80 or 90 percent of the planted area of most crops. Four strategies have been developed to cope with estimating crop area, crop yield, and total crop production in the case of intercropping situations. Strategies 3 and 4 that use the whole plot as the denominator or proportionally allocate the plot area to each crop in the mixture, respectively, are most widely used. The main disadvantage of strategy 3 is that it does not allow for aggregating crop areas at a higher level, whereas the main disadvantage of strategy 4 is that is does not allow for assessing the impact of intercropping on crop yields. Where three or more crops are in a mixture, it is suggested that data collection be limited to the two principal crops in the mixture. No strategies have yet been developed to take into account more complex intercropping situations, such as relay cropping and the mixing of annual with seasonal crops.

### Crops with an Extended Harvest Period

Crops that have an extended harvest period, such as cassava, sweet potato, banana, cotton, coffee, and indeterminate legumes, pose a problem in crop yield studies. But even crops such as maize and beans may be harvested at two or more stages (green maize and dry maize). Extended harvest periods may be the result of better in-ground than out-of-ground storability (cassava, sweet potato), continuous planting (all crops), uneven ripening or filling (banana, cassava), and multiple harvest products from one crop (green and dry maize). Except for the UBOS studies comparing farmer recall with the crop card methodology (Carletto et al. 2010; Sempungu 2010), no studies have been found that evaluate various methods to estimate yields for crops with an extended harvest period. All studies discussed earlier that compared crop cuts with farmer estimates were based on cereals.

Crop cuts and whole plot harvesting do not take into account the extended harvest period of the crop under study. They are carried out at one given moment in time when the crop is assumed to have matured. If harvesting is always done at the same time after planting (say, 12 months after planting for cassava), the resulting crop yields can be compared across regions and years and, when obtained through a whole plot harvesting exercise, may be regarded as the most objective yield measurement that can be obtained for this type of crop. Crop cuts and whole plot harvesting cannot be used to estimate banana yield due to its uneven ripening throughout the year. As discussed above, Wairegi et al. (2009) developed a method to estimate banana bunch weight on individual plants in East Africa using nondestructive field observations and an allometric relation that is valid for a range of genotypes and agroecologies.

Doubting farmer recall estimates for crops with an extended harvest period, Murphy, Landell, and Wahlstedt (1991) suggest that yield estimates of root and tuber crops can only be obtained through a case-study approach, whereby crop yields are determined in a selected number of fields using the crop-cut method. Total production can then be estimated by multiplying the average yield level with the number of cultivated plots observed in the full survey. A similar approach can be used for banana using the allometric method. For cotton and coffee, it may be possible to obtain purchase records from processing or exporting companies.

No evidence was found that farmers are unable to estimate yields of crops with an extended harvest period. Fermont et al. (2009), who asked farmers to estimate crop yield for a well-known area in order to triangulate results with crop areas, consumption, and selling patterns, observed in Uganda and Kenya that farmer estimates of average cassava yield were on average 15 percent lower than crop cuts in on-farm trials using recommended plant spacing and timely planting. Taking into account the use of improved agronomic practices in the on-farm trials and that *economic yield* data are lower than *harvested yield* data, the small difference suggests that farmers are able to accurately estimate the yield or production of crops with an extended harvest period if they are motivated to do so. The crop-card method has been developed to aid farmer recall for such crops. Observed problems, such as illiterate farmers, limited sample size for national surveys, poor follow-up, and an increased likelihood of data entry errors, and possible solutions with this method will have to be weighed against the disadvantages and advantages of farmer recall.

### Planted Area Not Being Equal to Harvested Area

Crop area may be defined as either the area planted or the area harvested. The planted area may not be equal to the harvested area for a variety of reasons, including poor germination, pest or disease damage, animal grazing, floods, lack of labor, or a lack of market. In addition some crops, such as cassava, may be grown as an insurance measure and only fully harvested in cases of drought or food shortage. In any of the above circumstances, the definition of crop area that is used has a large influence on area, yield, and production estimates.

***Situation A*: Crop Area = Harvested Area; Yield Estimate Based on Harvested Area**

Casley and Kumar (1988) argue that harvested area is always the most relevant area measurement to use, both for reporting crop area as well as for estimating crop yield at the individual plot level. Crop production at farm, stratum, or national level can then automatically be computed as

$$\text{Crop production} = \text{harvested area x yield per harvested area,} \tag{6}$$

whereby yield data can be obtained from methods that are based on the harvested area (that is, crop cut and whole plot harvesting).

***Situation B*: Crop Area = Planted Area; Yield Estimate Based on Harvested Area**

For practical reasons, most agricultural surveys and censuses will record crop area as planted area instead of harvested area. Where yield estimations are based on harvested area, crop production should then be computed as

$$\text{Crop production} = \text{planted area x yield per harvested area x \% area harvested,} \tag{7}$$

whereby the planted area for each stratum and crop is corrected downward by an estimate of the percentage of area that has been actually harvested. Such a correction factor may be determined from a subsample of holders for each stratum.

***Situation C*: Crop Area = Planted Area; Yield Estimate Based on Planted Area**

Alternatively, yield estimates that are based on planted area can be used (such as daily recording, sampling harvest units, farmer recall, and crop cards) and crop production is computed as

$$\text{Crop production} = \text{planted area x yield per planted area.} \tag{8}$$

In all cases, the survey or census report should clearly indicate how crop area and crop yield were defined.

## Level of Aggregation

Sampling strategies for the agricultural censuses in Uganda have always been based on stratification by regions, districts, or sub-counties to facilitate organization and logistics. The ongoing subdivision of Uganda in more and more districts very likely will reduce the number of surveyed agricultural households per district and negatively affect sampling precision at the district level. A more serious objection against stratifying at the district level was pointed out by Belshaw (1982) and Hall (1972). Aggregating data from agricultural households at the district level obscures information about the major farming systems in Uganda, as these farming systems cut across administrative boundaries. Use of administrative units for data analysis will hinder effective examination of trends in crop production and productivity at the farming system level and the development of appropriate policies and research and extension efforts to address constraints to productivity within particular farming systems. An added advantage of stratification by major farming systems is that the boundaries are not affected by future changes at the administrative level, such as further subdivision of districts, and results thus will remain comparable between censuses. However, admittedly there are significant challenges in appropriately spatially defining farming systems and then implementing agricultural censuses and surveys on the basis of this farming system geography.

## Variation in Crop Yield over Time

An agricultural survey or census generates crop yield data that are–if sampling and non-sampling errors are not too large–an accurate representation of crop yield in a specific season or year. Crop yields are determined by many factors. Direct factors include, among others, crop variety, rainfall, soil fertility, crop management, and pests and diseases, whereas agricultural policies, such as fertilizer subsidies, available infrastructure, and the presence of development projects may indirectly influence crop yields. Year-to-year variations in rainfall, pests and diseases, and policies may cause large variations in crop yields, whereas soil fertility, crop management, and available infrastructure will have a more structural, longer-term impact on crop yields.

In an environment where output is highly dependent on rainfall, it is difficult to draw any conclusions about causality in either cross-section or time-series analyses without referring to or controlling for rainfall (Diskin 1997; Kelly et al. 1995). Even for a drought-tolerant crop such as cassava, rainfall explained 30 percent of the observed variation in two-year yield data in Uganda and Kenya (Fermont et al. 2009). Using the Zimbabwe data from Casley and Kumar (1988; see Table ), it can be calculated that observed differences in maize yield between the lowest and highest yielding regions were around 55 percent in the first year and around 210 percent in the second year, with little variation between methodologies. As yield estimations from crop cuts were on average 81 percent and 37 percent higher than farmer estimates in the first and second year, it can be concluded that the observed variability in maize yield due to agroecological conditions is of the same order of magnitude, or even higher, than the bias introduced by the choice in crop yield estimation method.

# 8. CONCLUSIONS ON METHODS TO ESTIMATE CROP YIELDS

## General

This literature review shows that a wide range of methodologies has been developed to estimate crop production, area, and, ultimately, yields in the fields of smallholder farmers. It also shows that there is very little conclusive empirical evidence of the magnitude of biases and their determining factors across the various methodologies. Most evaluations are based on anecdotal evidence and logical reasoning.

As discussed, each method has its own advantages and disadvantages. Table 8.1 provides an overview of each that includes, among others, sampling and non-sampling errors and biases, cost and time requirements, and the ability to account for multiple harvesting patterns. The statistical benefits of a random sampling strategy should be balanced against the logistical and economic benefits of a stratified sampling strategy.

For crop production estimates, in small-scale, intensive diagnostic studies, complete harvesting avoids many biases and random errors associated with crop cuttings and may therefore be the best method (Casley and Kumar 1988; Poate 1988). Crop cuts are appropriate for studies that require moderate levels of detail, for situations that farmer recall does not give sufficiently precise results, and for larger-scale surveys for which sufficient financial resources have been obtained. For the purpose of agricultural censuses or national surveys, arguments in favor of using farmer production estimates instead of the more widely accepted crop-cut method include similar levels of bias or accuracy; the statistical benefits of random sampling over cluster sampling; and lower cost and less time. Whichever method is chosen, one should keep in mind that methods estimate different definitions of yield and almost all methods require corrections to standard harvest states and units.

To estimate crop areas, the polygon method is the most accurate method. However, it is labor-intensive. GPS area estimates are fairly accurate for larger plots; however, their use is limited on the smaller plots that many smallholders farm, in hilly areas, or in areas with dense tree cover. In cases of such restrictions or limited time or finances, farmer estimates are a good alternative. As discussed, the accuracy of farmer estimates of crop area can be improved in various ways. The $P^2/A$ method has only been tested in Rwanda. Considering the positive results obtained, the appropriateness of this method for estimating areas of small plots of less than 0.5 ha should be tested in Uganda.

As Poate (1988) stated, there is no best method for estimating production, area, and yield. The appropriateness of the each method depends on the scale of measurement, as well as on project objectives and available resources.

## Agricultural Statistics in Uganda: Some Suggestions

With the aim of improving data quality of future crop yield estimations in agricultural censuses or national agricultural surveys, in this subsection suggestions are made concerning the most appropriate methods to estimate crop production, area, and yield in the context of agricultural censuses and surveys in Uganda.

**Table 8.1—Advantages and disadvantages of methods to estimate crop production and crop area**

| | | Non-sampling errors[a] | | | | | | | | | Yield concept measured[b] | | | Level of detail | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Sampling error due to clustered sampling[a] | Measurement bias | Measurement error | Response bias | Response error | Bias due to use of conversion units | High costs / high time requirement | Accounts for multiple harvests | Influenced by heterogeneous crop | Crop area is integrated in production estimation | Biological | Harvested | Economic | Plot | Farm | Village |
| Crop production | | | | | | | | | | | | | | | | |
| Crop-cuts | ++ | ++ | + | - | - | + | ++ | N | ++ | Y | S | N | N | S | N | N |
| Farmer recall | - | - | - | + | + | ++ | - | (S) | - | N | N | N | S | S | S | N |
| Daily recording | ++ | + | ++ | - | - | + | ++ | S | - | N | N | N | S | S | S | N |
| Whole plot harvest | ++ | + | + | - | - | + | ++ | N | - | Y | N | S | N | S | N | N |
| Sampling harvest units | + | + | + | - | - | + | + | N | - | N | N | S | S | S | S | N |
| Expert assessment | - | + | - | - | - | - | - | N | + | N | S | N | N | S | N | N |
| Crop-card | + | - | - | + | + | ++ | + | S | - | N | N | N | S | S | S | N |
| Crop modeling | - | - | - | - | - | - | + | N | - | Y | S | N | N | N | (S) | S |
| Purchase records | - | - | - | - | - | - | - | S | - | N | N | N | S | N | (S) | S |
| Allometric models | + | - | + | - | - | + | + | N | ++ | N | S | N | N | S | N | N |
| Remote sensing | - | - | ++ | - | - | + | + | N | + | Y | S | N | N | N | (S) | S |
| Crop area | | | | | | | | | | | | | | | | |
| Polygon method | ++ | - | - | - | - | - | ++ | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | S | N | N |
| Rectangulation | ++ | -/+ | - | - | - | - | + | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | S | N | N |
| P2/A method | + | - | + | - | - | - | - | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | S | N | N |
| GPS | + | - | ++[c] | - | - | - | - | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | S | S | N |
| Remote sensing | - | - | ++[c] | - | - | - | + | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | N | S | S |
| Farmer assessment | - | - | - | + | ++ | -/+ | - | n.a. | n.a. | n.a. | n.a. | n.a. | n.a. | S | S | N |

Source: Author compilation.
Notes: Y = yes; N = no or not suitable; S = suitable; n.a. = not applicable; - = likely unimportant; -/+ = sometimes important; + = likely important; ++ = likely very important.
[a] See Sections 3 and 6 for details on sampling and non-sampling errors and biases.
[b] See Section 1 for details on different yield concepts.
[c] Larger plots only.

## Lessons from Past Censuses

### *1965 Agricultural Census*

The 1965 census used labor-intensive methods for data collection–the daily recording of harvest products on a subsample of farmers to estimate crop production and rectangulation and triangulation for crop area estimation. The daily recording method ensured that harvests were recorded as economic yield, with little losses due to eating and selling, and there was no need to use local weight conversion units with the potential for large non-sampling errors that such quantity conversions involve. However, due to its high labor requirements and the necessary clustered sampling strategy, the number of plots from which crop yield data were obtained was extremely small for certain crops in certain areas. Consequently, it was recognized that certain crop yield data might be expected to have (very) high sampling errors (MAC 1967). Non-sampling errors were probably important as well because the national conversion factors that were used to convert local states of harvest and weight units to standard units were based on small subsamples and the required analyses and calculations were done by enumerators instead of trained field technicians (Muwanga-Zake 1985). This was realized in the census report, which therefore recommended that more work was required to develop local unit to standard unit conversion factors with a higher degree of accuracy (MAC 1967).

The strong points of the 1965 census included using planted area as the basis for data collection in both the crop area and the crop yield survey, so no error was introduced when national production levels were estimated. That the intercrop constituency for each sample plot was recorded was also useful. This permitted the average impact of intercropping on crop yield to be taken into account when computing total crop production and the impact of intercropping on crop yield could be evaluated.

### *1990/91 Agricultural Census*

The 1990/91 census used crop cuts to estimate crop yields, whereby the subplots were demarcated long before the actual harvest, which created some practical problems (MAAIF 1992). More serious problems are related to the likely important levels of sampling and non-sampling errors due to the limited number of plots per crop of between 9 and 40 per district; the likely mixture of data from pure and mixed plots; poor capturing of field heterogeneity with only one generally quite small subplot per field; the use of obscure local harvest quantity units that were difficult to convert to standard weight or volume units; and the use of 25 kg weighing scales to capture harvest weights of a few kilograms only.

### *2008/09 Agricultural Census*

Although details on the full sample design and field operations of the 2008/09 census are not yet publicly documented, sampling error in the census can be expected to be lower than for previous censuses due to the much larger sampling frame. The largest sources of non-sampling error can be expected to originate from the use of national conversion units to convert local weights to standard weights and some incidence of poor quality responses due to the length of the total interview.

## Combining Methodologies

Estimating crop yield and production at regional or national levels with a high degree of sampling precision requires fairly large dispersed samples. This may not be feasible with any method that uses actual measurement, and the most appropriate method in many such circumstances may be farmer estimation methods. Evidence is accumulating that estimates by farmers do not necessarily result in a larger total error than that obtained using the crop-cut method. This said, the most appropriate method for aggregate yield estimates also depends on crop type. Many national statistical agencies use a combination of methodologies to capture crop yields of various crops with the highest level of accuracy.

For seasonal crops like cereals and grain legumes, farmer production and farmer area estimates in a randomized large survey may be the most appropriate methodology. However, for root and tuber crops, crop cuts at a standard age (12 months for cassava; 8 months for sweet potato and Irish potato) in combination with a randomized large survey to estimate the number and size of plots may be more appropriate. Due to its staggered ripening throughout the year, banana is the most problematic crop from which to obtain yield estimates. Allometric methods may be useful for banana but need further testing. The crop-card method, which was developed to capture production of crops with an extended harvest period, seems to have several practical problems associated with its use. But if these can be overcome, the method may prove to be an alternative to crop cuts for root and tuber crops and allometric methods for banana.

### Improving Quality of Farmer Recall Data

In a well designed and carefully executed survey or census, farmer recall data may have very acceptable levels of total error. However, there are many sources of bias and error that may reduce data reliability, if not properly addressed. The following are suggestions through which the quality of farmer recall data can be substantially improved:

- Conduct an awareness-raising campaign with farmers at the start of an agricultural census to reduce deliberate over- or underreporting. Farmers will be more aware of the survey objectives and how the information will be used.
- Keep interviews sharply focused by reducing the number of questions to a minimum in order to prevent fatigue on the part of farmers and enumerators. The 2008/09 census forms appear to be too long and may result in poor levels of accuracy in the responses obtained, due to interview fatigue affecting both the respondent and the enumerator. Breaking long interviews into two or more separate sessions may help in this respect, but this can only be done at the expense of logistical efficiency in the administration of a survey or census.
- Motivate enumerators to visit all cropped plots with the farmer and encourage them to discuss crop area estimations with the farmer.
- Using farmer recall and crop area estimates, calculate crop yields during each interview and ask farmers to explain abnormally high or low yields (Rozelle 1991).
- Triangulate data on production, consumption patterns, marketing patterns, and the like immediately after the interview and directly cross-check possible inconsistencies. A few standard triangulation questions may be built into the survey or census questionnaires.
- Instead of having farmers estimate crop production and crop area separately, thereby introducing two sources of error, ask farmers to estimate crop yield for a well-known unit area that can easily be measured by the enumerator. In many cases, the farm compound serves as a good unit area (Fermont 2009). Alternatively, if standard land units are used in an area, the enumerator may choose to use such units as the unit area respondent farmers will use to estimate crop yields.
- Reduce omissions in production estimates of consideration of in-kind gifts and payments made from household crop production by including specific questions on such crop produce flows off of the farm.
- Structurally determine conversion factors for all reported harvest units at district or sub-county levels, thus reducing the errors introduced by the use of national average conversion factors. To prevent measurement errors in deriving these conversion factors, this task should be done by trained field staff under close supervision.
- Cross-check and improve data quality of farmer estimates through the use of small sets of detailed studies on subsamples within the survey. For these subsamples, crop cuts and the $P^2/A$ or the polygon method may be used to estimate crop production and area. If deemed necessary, using the correlation between estimated and measured values, correction factors can be defined to improve data quality. Preferably, crop cuts should be carried out on two subplots per plot that are large enough to capture the within-plot variability in crop performance.

### *Improving Crop Yield Interpretation*

Gathering good quality yield data is not easy. Neither is interpreting them. As discussed earlier, crop yields are determined by many factors. Here we describe several approaches to making the interpretation of crop yields and the identification of regional or temporal trends in production and yield levels somewhat easier.

#### *Stratification: Farming Systems, Regions, or Districts*

There is considerable demand for agricultural statistics in Uganda to be presented by district in order to fulfill data requirements of local government planning activities that are structured according to districts. Presentation of data by district also fulfils the data requirements of many development partners of the Ugandan government that generally organize their activities by district. However, the larger on-farm survey and census exercises that have been carried out in Uganda have not provided district-level information. Rather, they have been stratified by region, such as the Agricultural Policy Secretariat surveys in 1997 and 1999 (APS 1999; APS 1997); or stratified by farming systems, such as the cost of production surveys carried out by the Uganda Agricultural Productivity Enhancement Program (APEP) and the Livelihoods and Enterprises for Agricultural Development (LEAD) program, projects supported by the US Agency for International Development between 2005 and 2010 (pers. comm., P. Wathum, November 2010); or stratified by agroecological potential, such as the Research on Poverty, Environment, and Agricultural Technologies (REPEAT) survey of Uganda's Makerere University and Japanese agricultural researchers (Yamano et al. 2004).

From an agroecological point of view, crop yields are best estimated and presented by farming system as this best captures variability in climate, soils, and cropping practices in more or less homogeneous units. In colonial times, Uganda was divided into seven broad agroecological zones or agricultural systems: (1) Teso system of east central Uganda; 2) banana and coffee system; (3) banana, millet, and cotton system; (4) Northern system; (5) West Nile system; (6) Montane system; and (7) pastoral system (Parsons 1970). This geography of agriculture in Uganda was based on ecology–notably, annual rainfall patterns (equitable rainfall versus areas with a pronounced dry season) and altitude–and the social history and background of the Ugandan people. Although the importance of many crops has changed over time–for example, maize and cassava have become dominant crops in many areas of Uganda over the past 50 years, whereas the importance of cotton and finger millet has declined–this old farming system geography of agriculture in Uganda is still in use (Mwebaze 1999).

It is suggested that in future agricultural censuses and surveys, where the desired sample size allows, the sampling frame be designed in such a way that estimates can be presented both according to district as well as according to farming system. Districts that cover more than one farming system should be sampled in such a way that the major farming systems found in the district are proportionally represented in the census or survey design. The ideal sampling frame should also allow for repetitive annual data collection exercises.

Designing the sample for a survey or census so that estimates can be made by farming system should reduce the variation in crop yields due to variable agroecological conditions, while providing for an increase in the number of observations per stratification unit. Both will result in a lower total error and, therefore, more accurate results.

#### *Weather Data*

In an environment where output is highly dependent on rainfall, it is difficult to draw any conclusions about causality in either cross-section or time-series analyses without referring to rainfall. None of the agricultural statistical reports in Uganda present basic weather data along with crop yield data, which hinders proper interpretation of the data. It is recommended that basic weather data (monthly rainfall data and total annual rainfall) are included in future reports on agricultural statistics. A minimum of one weather station, though preferably more, per farming system is suggested.

***Intercropping***

Intercropping has a major impact on crop yields. The 1965 census and 1967/68 surveys presented crop yields by intercropping system, which allowed for the interpretation of the impact of intercropping on crop yields (reductions of up to 45 percent in cereal yields were observed in the 1965 census) and improved the estimation of total crop production at national and district levels. Unfortunately, the 1990/91 census did not report any information on intercropping systems, while the agricultural modules of the UNHS only indicate average percentage of plots under pure stand.

It is suggested that in future agricultural censuses or surveys, intercropping is taken into account. Following Kelly et al. (1995), it is recommended that only the two principal crops in an intercropped field be accounted for. Thus it will be useful to include a minimum percentage (say, 20 percent of plot area occupied by a crop) before a crop is counted as an intercrop. Some serious thought should be given to whether strategy 3–using the whole plot as denominator for each crop in the mixture–or 4–allocating part of the plot size to each crop in the mixture–to estimate crop production under intercropping is most appropriate for the Ugandan context to account for the impact of intercropping practices on crop yields and total production.

# APPENDIX: OBSERVED YIELDS OF SELECTED CROPS IN UGANDA

## Database on Crop Yields for Uganda

A central element of the study from which this report was developed was to undertake a thorough literature review and consultations to assemble a database of the yields recorded for a selection of crops primarily grown by smallholder farmers in Uganda – maize, sorghum, finger millet, rice, banana, cassava, Irish potato, sweet potato, groundnuts, and beans. The information collected has been collated into a multi-sheet Excel file that is an important supplementary set of information to this report. Whenever possible, it is intended that this database will be distributed together with this report. This crop yield database is available as a separate Excel file upon request from the IFPRI-Kampala office (IFPRI-Kampala@cgiar.org).

The sources of the yield data consulted for the database are summarized in Table A.1. One of the datasheets in the database provides full information on each source consulted. Each record of crop yields in the database includes a reference to the source of the data. While the database development involved extensive searches in agricultural libraries in Uganda and consultations with crop experts, it is recognized that not all sources were considered. As such the database should be regularly updated in the future with data from sources that were inadvertently omitted in the initial database compilation exercise and from new estimates made in conducting future field research or agricultural surveys and censuses.

**Table A.1—Types of sources consulted in developing the database of crop yields for Uganda**

| Type of data source | Number of sources | Earliest | Latest |
|---|---|---|---|
| Reports from the National Agricultural Research Organisation, (NARO) from specific research stations, or from specific NARO research programs | 24 | 1987 | 2007 |
| Makerere University – BSc, MSc, and PhD theses | 36 | 1975 | 2009 |
| Uganda Journal of Agricultural Science | 8 | 1993 | 2005 |
| Articles in other academic journals | 43 | 1992 | 2010 |
| Project reports and working papers from nongovernmental organizations, agricultural research institutes, and other nongovernmental research institutes | 32 | 1988 | 2010 |
| Official agricultural statistics reports from the Ministry of Agriculture, Uganda Bureau of Statistics, and other agencies | 14 | 1967 | 2009 |
| **Total** | **157** | | |

Source: Compiled by authors.

Sources were consulted that contained information either from Uganda or from locations in the broader region with agroecologies comparable to those found in Uganda (Kenya, Tanzania, Rwanda, and so forth). The information is presented in the database in individual crop-specific data sheets. Data records in each sheet are grouped into five sections either by geography or by major sources of such crop yield information for Uganda. These five sections are

1. Uganda (generic),
2. similar agroecologies (generic),
3. estimates from Uganda agricultural censuses,
4. estimates from Uganda National Household Survey, and
5. estimates provided by the Ministry of Agriculture, Animal Industries, and Fisheries (MAAIF).

Each of these five sections is further subdivided by the method used to estimate the crop yields presented–crop cuts, farmer estimates, and other methods. For some crops, the methods used are further subdivided by the context in which the crop was grown–on-farm or on an agricultural research station. Each crop yield estimate record in the database contains most of the information presented in Table A.2. The level of detail varies considerably between sources, with reports from crop research trials typically giving the most detail.

**Table A.2—Information recorded in the database of crop yields for Uganda**

| Data field | Notes |
|---|---|
| Reference number | Refers to a list of data sources provided in datasheet in the database |
| Crop | Crop name |
| Research context | For what purpose were crop yield levels estimated? |
| Trial or survey information | Brief description of trial or survey from which yields were estimated |
| Production estimation method | Crop cut, farmer estimation, or details on other methods used |
| Area estimation method | Such as measured by rectangulation or GPS, farmer estimate, or rectangular trial plot |
| Trial set-up | For agricultural trials, the treatment plot lay-out |
| Country | Country from which yield estimates were obtained – Uganda or a neighboring country |
| Region/district | Region or district from which yield estimates were obtained |
| Year | Year in which the crop from which yield estimates were obtained was grown |
| Sample size (n) | Number of plots of the crop sampled for yield estimate calculation |
| Average yield (t/ha) | Average yield estimated in metric tonnes per hectare |
| Yield range (t/ha) | Range in yields estimated from the plots sampled |
| Standard deviation | Standard deviation in yield estimates across plots sampled |
| Variety | Whether the crop grown was an improved or local/traditional variety |
| Fertilizer | Information on whether the crop was fertilized |
| Management | Information on the management regime for the crop – traditional, low input, or high input; farmer or researcher managed; pure or mixed (intercropped) stand, and so on. |
| Agroecology | Any information on the agroecology in which crop was grown |
| Rainfall (mm) | Amount of rainfall during the cropping season when the crop from which yields were estimated was grown |
| Soil type | Soil conditions in which crop was grown – soil taxonomy categories or simply soil texture |
| Farm type | If yield estimates derived from on-farm crop production, indicates whether farmers who grew crop were representative of most farmers or were a special group |
| Comparison with other literature | Notes on whether yield estimates recorded confirm or conflict with other estimates |
| Other information | Other pertinent contextual information about cropping conditions for the crops from which yields were estimated, including any assumptions made in the estimation process and notes on problematic areas related to the yield estimates obtained |
| Standard *state of harvest* | State of harvest of crop used to estimate yields – moisture content, shelled or not, with stalk or not, and so on |
| *State of harvest* conversion factors used | If crop harvest was not harvested in the standard state, what conversion factors were used to adjust yields calculated to the standard state |

Source: Compiled by authors.

Aggregate yield estimates by crop have been drawn from the database and are presented in the tables below. The first group of tables provides estimates based on estimation method and management level – on-farm surveys using farmer recall to estimate yields (Table A.3), on-farm research trials using crop cuts (Table A.4), and on-station trials using crop cuts (Table A.5). Table A.6 presents the crop yield estimates obtained from a mixed quantitative and qualitative method approach to estimating yields carried out as part of cost of production surveys for the USAID-supported APEP and LEAD projects between 2005 and 2010.

**Table A.3—On-farm surveys (farmer recall): Average yield and yield range of selected crops, by variety type and fertilizer use, t/ha**

| | Local varieties | | | | Improved varieties | |
|---|---|---|---|---|---|---|
| | Unfertilized | | Fertilized | | Unfertilized | |
| | n | yield | n | yield | n | yield |
| Maize | 3,421 | 1.2 (0.7-1.7) | … | … | 3,723 | 2.1 (1.1-2.9) |
| Sorghum | 2,661 | 1.2 (0.3-2.3) | … | … | 90 | 1.2 |
| Millet | 3,262 | 1.2 (0.3-2.7) | … | … | … | … |
| Rice | 4,127 | 1.7 (1.4-2.2) | … | … | … | … |
| Banana (farmer recall) | 4,843 | 7.4 (1.2-25.8) | … | … | 2,573 | 8 (6.4-10.9) |
| Banana (other methods) | 253 | 14.1 (6.6-25.5) | 143 | 25.5 (19.7-32.6) | … | … |
| Cassava | 4,308 | 6.3 (2.6-12.7) | … | … | … | … |
| Irish potato | 2,231 | 6 (2.5-9.0) | … | … | … | … |
| Sweet potato | 3,965 | 4.6 (3.2-6.5) | … | … | … | … |
| Groundnut | 2,806 | 0.6 (0.2-0.8) | … | … | 4,958 | 0.8 (0.6-0.9) |
| Bush bean | 4,198 | 0.9 (0.4-2.3) | … | … | 3,681 | 1.1 (0.9-1.2) |

Source: Compiled by authors based on database of crop yields in Uganda.
Note: Yield range shown in parentheses.

**Table A.4—On-farm trials (crop-cut): Average yield and yield range of selected crops, by variety type and fertilizer use, t/ha**

| | Local varieties | | | | Improved varieties | | | |
|---|---|---|---|---|---|---|---|---|
| | Unfertilized | | Fertilized | | Unfertilized | | Fertilized | |
| | n | yield | n | yield | n | yield | n | yield |
| Maize | 3,309 | 1.8 (1.2-2.4) | 16 | 4.5 | 697 | 2.4 (1.5-3.7) | 3,318 | 4.3 (3.0-5.5) |
| Sorghum | 630 | 1.2 (1.0-1.4) | … | … | … | … | 600 | 2.7 |
| Millet | … | … | … | … | 447 | 0.9 (0.5-1.6) | 9 | 2.2 |
| Rice | 2,400 | 1.6 | … | … | 41 | 1.7 | 2,405 | 3.4 (3.3-3.5) |
| Banana | 52 | 16.2 (8.2-26.1) | 9 | 16.5 (3.1-31.9) | 32 | 22.6 (19.4-25.9) | … | … |
| Cassava | 439 | 12.5 (4.7-31.2) | 18 | 14.4 | 1,215 | 12.9 (11.3-34.6) | 63 | 23.1 |
| Irish potato | … | … | 24 | 12.4 | 139 | 21.6 | 24 | 17.6 |
| Sweet potato | 307 | 8.5 (3.5-13.4) | … | … | 55 | 10.1 (8.1-12.0) | 300 | 6.6 |
| Groundnut | 2,700 | 0.8 | … | … | … | … | 2,716 | 1.6 (1.2-2.0) |
| Bush bean | 1,643 | 0.9 (0.5-1.2) | … | … | 1,803 | 0.8 (0.3-1.6) | … | … |

Source: Compiled by authors based on database of crop yields in Uganda.
Note: Yield range shown in parentheses.

**Table A.5—On-station trials (crop-cut): Average yield and yield range of selected crops, by variety type and fertilizer use, t/ha**

| | Local varieties | | | | Improved varieties | | | |
|---|---|---|---|---|---|---|---|---|
| | Unfertilized | | Fertilized | | Unfertilized | | Fertilized | |
| | n | yield | n | yield | n | yield | n | yield |
| **Maize** | … | … | … | … | 19 | 3.8 (0.9-5.5) | … | … |
| **Sorghum** | … | … | 12 | 3.5 | 18 | 2.2 (0.7-3.2) | … | … |
| **Millet** | … | … | … | … | 2 | 0.6 (0.5-0.7) | 12 | 2.2 (1.4-2.9) |
| **Banana** | 34 | 12.9 (7.7-16.1) | 17 | 13.6 (5.7-21.5) | … | … | … | … |
| **Cassava (agronomy trials)** | 80 | 12.3 (9.4-15.1) | … | … | 220 | 13.7 | … | … |
| **Cassava (breeding trials)** | 60 | 33.8 | 48 | 10.5 | 507 | 28.7 (18.8-38.4) | 128 | 12.81 |
| **Irish potato** | 25 | 16.7 (12.5-24.4) | … | … | 30 | 21.6 (7.8-42.0) | … | … |
| **Sweet potato** | 30 | 16.1 (4.6-26.5) | … | … | 20 | 15.8 (9.4-22.3) | … | … |
| **Groundnut** | … | … | … | … | 9 | 1.1 | 4 | 1 |
| **Bush bean** | … | … | … | … | 127 | 1 (0.5-2.3) | … | … |

Source: Compiled by authors based on database of crop yields in Uganda.
Note: Yield range shown in parentheses.

**Table A.6—Cost of production surveys by APEP and LEAD projects: Average yield and yield range of selected crops, by variety type and fertilizer use, t/ha**

| | Local varieties | | Improved varieties | | | |
|---|---|---|---|---|---|---|
| | Unfertilized | | Unfertilized | | Fertilized | |
| | n | yield | n | yield | n | yield |
| **Maize** | 126 | 1.7 (1.2-2.5) | 152 | 3.3 (2.1-4.4) | 142 | 6.7 (5.4-8.3) |
| **Sorghum** | 14 | 1.1 (1.0-1.2) | 14 | 2.3 (2.0-2.7) | … | … |
| **Millet** | 26 | 1.1 (0.7-1.6) | 24 | 1.9 (1.7-2.2) | 2 | 4 |
| **Rice** | 90 | 1.9 (1.0-2.7) | 94 | 3.5 (2.5-5.9) | 74 | 5.8 (4.4-8.6) |
| **Banana** | 27 | 11.2 (10.8-11.5) | 27 | 48.3 (44.3-52.4) | 18 | 68.7 (65.6-71.9) |
| **Cassava** | 32 | 5.6 (3.7-8.6) | 30 | 10.4 (7.4-18.5) | 2 | 18.5 |
| **Sweet potato** | 24 | 4.4 (3.7-4.4) | 24 | 7.9 (6.2-9.9) | … | … |
| **Groundnut** | 3,965 | 4.6 (3.2-6.5) | 26 | 1.2 (0.5-1.5) | 12 | 1.8 (1.2-2.2) |
| **Bush bean** | 2,806 | 0.6 (0.2-0.8) | 28 | 1.5 (0.5-2.1) | … | … |

Source: Compiled by authors based on database of crop yields in Uganda.
Note: Yield range shown in parentheses.

As was discussed at length earlier, national agricultural censuses and surveys, agricultural modules in regular national household surveys, and annual reports from the Ministry of Agriculture, Animal Industries and Fisheries all provide estimates of average national crop yields in Uganda. A summary from these national statistical sources is presented in Table A.7.

**Table A.7—Agricultural censuses, annual agricultural statistical surveys, agricultural modules of the UNHS, and annual national estimated by Ministry of Agriculture, Animal Industries and Fisheries: Average yield and yield range of selected crops, t/ha**

| | Agricultural censuses & annual agricultural statistical surveys | | | | | | | | Uganda National Household Survey (UNHS) | | Ministry of Agriculture annual estimates |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1965 | | 1967/68 | | 1968 | | 1990/91 | | 1999 | 2005/06 | 1970-2009 |
| | n | yield | n (min.) | yield | n (min.) | yield | n | yield | yield | yield | yield |
| **Maize** | 556 | 0.9 (0.4-1.6) | 198 | 1.4 (1.0-2.2) | 216 | 1.4 (1.0-2.4) | 1,040 | 1.5 (0.5-3.3) | 1.1 (0.4-1.7) | 1.6 (1.1-2.5) | 1.5 (1.3-1.8) |
| **Sorghum** | 416 | 0.7 (0.2-1.2) | 171 | 1.2 (0.8-1.7) | 216 | 1.3 (0.8-1.9) | 960 | 1.9 (1.0-2.8) | 0.7 (0.1-1.4) | 0.5 (0.2-0.9) | 1.4 (1.1-1.6) |
| **Millet** | 1,050 | 1.1 (0.4-1.8) | 162 | 1.1 (0.5-1.7) | 126 | 1.2 (0.8-1.7) | 1,040 | 1.5 (0.5-3.4) | 0.6 (0.4-1.0) | 0.7 (0.2-2.5) | 1.5 (1.1-1.8) |
| **Rice** | … | … | … | … | … | … | … | … | 0.9 (0.4-1.2) | 1.5 (0.4-2.5) | 1.4 (1.2-1.5) |
| **Banana** | 684 | 8.1 (5.3-11.9) | … | … | … | … | 960 | 5.9 (2.4-9.0) | 3.8 (0.6-9.4) | 3.0 (0.7-5.8) | 5.8 (5.4-7.3) |
| **Cassava** | … | … | … | … | … | … | 1,040 | 25.2 (10.2-37.2) | 3.0 (1.8-5.3) | 1.6 (1.0-2.4) | 8.2 (4.3-14.4) |
| **Irish potato** | … | … | … | … | … | … | 680 | 8.4 (5.0-10.9) | 3.1 (1.1-8.6) | 3.3 (0.4-4.2) | 7.0 (6.8-7.1) |
| **Sweet potato** | 786 | 7.4 (5.5-8.8) | … | … | … | … | 1,040 | 8.4 (5.1-11.2) | 4.3 (1.7-7.2) | 2.6 (1.6-4.2) | 4.3 (3.5-4.5) |
| **Ground-nut** | 419 | 1.0 (0.7-1.5) | 207 | 0.9 (0.6-1.3) | 171 | 0.9 (0.6-1.4) | 1,040 | 1.1 (0.6-1.6) | 0.5 (0.3-0.6) | 0.8 (0.4-2.0) | 0.7 (0.6-0.8) |
| **Bean** | 1,448 | 0.6 (0.4-0.8) | 144 | 1.0 (0.5-1.6) | 108 | 1.0 (0.6-1.4) | 1,000 | 1.4 (0.6-2.4) | 0.8 (0.4-1.4) | 0.8 (0.5-1.0) | 0.6 (0.4-0.8) |

Source: Database of crop yields in Uganda compiled by authors.
Note: Yield range shown in parentheses.

The final group of tables below provides sub-national estimates of crop yields – either by administrative region or by natural region. Separate tables are presented based on the method by which crop production or yield was estimated. Average regional crop yields as estimated from farmer surveys using farmer recall methods to estimate production are presented in Table A.8 The next two tables, Table A.9 and Table A.10, present other estimates of average crop yields by administrative region based on crop-cuts from on-farm and on-station trials, respectively. The final table in this set of tables, Table A.1, provides estimates of crop yields by farming system that are aggregated from information collected in the cost of production surveys of the APEP and LEAD projects.

**Table A.8—Farm surveys (farmer recall): Average yield and yield range of selected crops by administrative region, t/ha**

| | Eastern | | Central | | Northern | | Western | |
|---|---|---|---|---|---|---|---|---|
| | n | yield | n | yield | n | yield | n | yield |
| **Maize** | 1,480 | 1.8 (0.8-2.5) | 2,648 | 1.4 (0.7-2.3) | 1,108 | 1.3 (0.6-2.0) | 2,117 | 1.6 (0.5-2.7) |
| **Sorghum** | … | … | 1,237 | 1 (0.3-1.6) | 554 | 1.1 (0.4-1.5) | 748 | 1.6 (0.8-2.3) |
| **Millet** | … | … | 1,331 | 0.8 (0.3-1.3) | 634 | 0.9 (0.5-1.1) | 787 | 1.6 |
| **Rice** | … | … | 2,959 | 1.7 (1.5-1.9) | 1,138 | 1.6 (1.4-1.9) | 30 | 2.2 |
| **Banana (farmer recall)** | 1,818 | 7.9 (3.9-14.2) | 2,373 | 6 (1.3-11.3) | 948 | 5.2 (1.2-7.3) | 1,693 | 10.8 (3-25.8) |
| **Banana (other method)** | 80 | 13.3 (7.0-20.4) | 87 | 8.7 (14.7-33.0) | … | … | 229 | 16.3 (6.6-25) |
| **Cassava** | 935 | 7 (2.6-12.7) | 1,097 | 6.6 (3.7-10.4) | 634 | 5.9 (5.5-6.2) | 957 | 5.8 (3.9-8.3) |
| **Sweet potato** | 915 | 5.2 (4.7-5.8) | 878 | 4.5 (4.3-5.0) | 554 | 4.2 (3.9-4.6) | 1,049 | 4.3 (3.5-5.2) |
| **Groundnuts** | 1,070 | 0.7 (0.5-0.8) | 2,402 | 0.5 (0.2-0.8) | 1,038 | 0.9 (0.5-1.5) | 1,262 | 0.7 (0.5-0.9) |
| **Bush beans** | 1,480 | 1 (0.7-1.5) | 1,756 | 0.8 (0.6-1.2) | 950 | 0.8 (0.5-1.1) | 1,705 | 1.1 (0.4-1.1) |

Source: Database of crop yields in Uganda compiled by authors.
Note: Yield range shown in parentheses.

**Table A.9—On-farm trials (crop-cuts): Average yield and yield range of selected crops by administrative region, t/ha**

| | Eastern | | Central | | Northern | | Western | |
|---|---|---|---|---|---|---|---|---|
| | n | yield | n | yield | n | yield | n | yield |
| **Maize** | 639 | 3.2 (1.8-5.5) | 69 | 2.3 (1.5-3.7) | … | … | … | … |
| **Millet** | 486 | 1.2 (0.5-2.2) | … | … | … | … | … | … |
| **Banana** | … | … | 37 | 13.7 (3.1-22.6) | … | … | 56 | 18.7 (8.2-31.9) |
| **Cassava** | 190 | 15.1 (6.2-19.0) | 286 | 16.3 (4.7-27.7) | 14 | 15.9 (10.9-20.8) | … | … |
| **Sweet potato** | 6 | 7 (4.6-10.1) | … | … | … | … | … | … |
| **Bush bean** | 23 | 0.4 (0.3-0.5) | 82 | 0.8 (0.5-1.0) | … | … | … | … |

Source: Database of crop yields in Uganda compiled by authors.
Note: Yield range shown in parentheses.

**Table A.10—On-station trials (crop-cuts): Average yield and yield range of selected crops by administrative region, t/ha**

| | Eastern | | Central | | Northern | | Western | |
|---|---|---|---|---|---|---|---|---|
| | n | yield | n | yield | n | yield | n | yield |
| **Maize** | 7 | 2.3 (0.9-3.8) | 6 | 4.4 (4.2-4.7) | … | … | … | … |
| **Millet** | 2 | 0.6 (0.5-0.7) | 12 | 2.2 (1.4-2.9) | … | … | … | … |
| **Banana** | … | … | 24 | 11.6 (5.7-15.3) | … | … | 27 | 15.1 (10.7-21.5) |
| **Cassava** | … | … | 416 | 12.4 (9.4-15.1) | … | … | … | … |
| **Sweet potato** | 6 | 7 (4.6-10.1) | 17 | 17 (9.3-22.4) | … | … | … | … |
| **Climbing bean** | … | … | 4 | 3.2 (2.9-3.4) | … | … | 30 | 1.4 (0.9-1.9) |

Source: Database of crop yields in Uganda compiled by authors.
Note: Yield range shown in parentheses.

**Table A.11—Cost of production surveys by APEP and LEAD projects : Average yield and yield range of selected crops by farming system, t/ha**

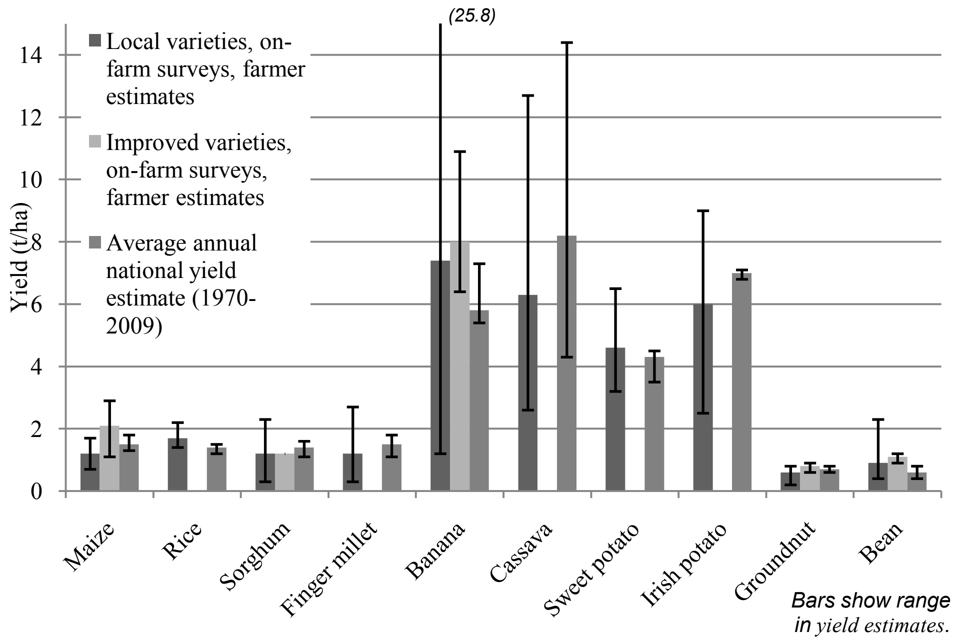
| | Montane | | Banana-Millet-Cotton | | Banana-Coffee | | Teso | | Unimodal & Lango | | Pastoral | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | n | yield | n (min.) | yield | n (min) | yield | n | yield | n | yield | n | yield |
| **Maize** | 28 | 2.7 (1.7-3.7) | 56 | 2.3 (13-3.5) | 46 | 2.9 (1.5-4.4) | 8 | 1.9 (1.2-2.7) | 20 | 1.8 (1.2-2.7) | 4 | 2.9 (2.0-3.7) |
| **Sorghum** | … | … | … | … | … | … | 6 | 2.1 (1.0-2.7) | 10 | 1.5 (1.2-2.1) | … | … |
| **Millet** | 4 | 1.6 (1.2-2.0) | … | … | 4 | 1.6 (1.2-2.0) | 4 | 1.2 (0.7-1.7) | 18 | 1.5 (1.0-2.2) | … | … |
| **Rice** | 10 | 3.5 (1.9-5.9) | 64 | 3.0 (2.0-4.1) | 4 | 2.0 (1.5-2.5) | 22 | 2.0 (1.0-3.0) | 4 | 2.0 (1.5-2.5) | … | … |
| **Banana** | … | … | 54 | 29.8 (10.8-52.4) | … | … | … | … | … | … | … | … |
| **Cassava** | 4 | 7.2 (4.4-9.9) | 10 | 8.2 (4.2-12.4) | … | … | 4 | 9.9 (7.4-12.4) | 20 | 8.6 (3.7-15.4) | 4 | 6.5 (4.4-8.6) |
| **Sweet potato** | … | … | 8 | 6.1 (3.5-9.9) | 4 | 5.9 (4.4-7.4) | 8 | 5.7 (3.9-8.6) | 4 | 8.1 (6.2-9.9) | 4 | 5.1 (3.7-6.4) |
| **Ground-nut** | 8 | 0.9 (0.6-1.2) | 8 | 0.9 (0.5-1.2) | … | … | 8 | 1.1 (0.6-1.5) | 14 | 0.7 (0.3-1.5) | … | … |
| **Bush bean** | 12 | 1.3 (1.0-1.8) | 4 | 1.5 (0.9-2.1) | 10 | 1.3 (0.7-2.0) | … | … | 6 | 0.6 (0.5-0.7) | 8 | 1.2 (0.7-1.7) |

Source: Database of crop yields in Uganda compiled by authors.
Note: Data on local and improved varieties, no fertilizer use; n = number of farmer groups that estimated cost of production, each farmer group consisted of about 20-30 farmers. Yield range shown in parentheses.

## Summaries of Yield Estimates in Uganda, by Crop

In the remainder of this section, summaries of the literature on crop yields in Uganda are presented on a crop-by-crop basis. Figure A.1 provides a graphical summary by crop of the average yields and range of yields estimated by farmers from all sources consulted in developing the database of crops yields for Uganda. The average annual national crop yields as estimated by MAAIF are also included in the figure.

**Figure A.1—Average yield and yield range of selected unfertilized crops observed in on-farm surveys (farmer recall) in Uganda, by variety, type, and average of annual national yield estimates (1970–2000)**




Source: Compiled by authors based on database of crop yields in Uganda.

### *Maize*

In farm surveys using farmer estimates, average unfertilized maize yields for local and improved varieties, respectively, are 1.2 (range of 0.7 to 1.7) and 2.1 (range of 1.1 to 2.9) t/ha. The 2004/05 UNHS estimates that about half (41 to 54 percent) of Ugandan maize fields are intercropped, planted as a mixed stand (UBOS 2007). Due to better management and pure stand planting, unfertilized maize yield estimates in on-farm trials for local and improved varieties, respectively, are 50 and 15 percent higher than farmer recall yield estimates at 1.8 (1.2–2.4) and 2.4 (1.5–3.7) t/ha. Fertilizer use increases maize yields in on-farm trials to between 4.3 and 4.5 t/ha.

Farmer recall yields are lowest for Northern Region (1.3 t/ha), followed by Central (1.4 t/ha), and Western (1.6 t/ha), and highest in Eastern Region (1.8 t/ha). Except for relatively low yields in the Teso system of eastern Uganda, unfertilized yields reported in the cost of production surveys by the APEP and LEAD projects show a similar pattern (pers. comm., P. Wathum, USAID/LEAD).

Average maize yield estimates reported by the agricultural censuses and annual surveys increase from 0.9 (0.4 to 1.6) t/ha in 1965 to 1.5 (0.5 to 3.0) t/ha in 1990/91. Average yield estimates reported in the UNHS increase from 1.1 t/ha in 1999/2000 to 1.6 t/ha in 2005/06, whereas MAAIF estimates the national average maize yield at 1.5 (1.3 to 1.8) t/ha for the period 1970–2009. Average maize yield estimates as reported by UBOS and MAAIF are within the range of yields reported by farmers in other studies.

### *Rice*

In farm surveys, farmers estimate average unfertilized rice yield of local varieties at 1.7 (range of 1.4 to 2.2) t/ha. The 2005/06 UNHS found that all rice fields in the survey sample were planted as a pure stand (UBOS 2007). With 1.6 and 1.7 t/ha yields for local and improved varieties, respectively, unfertilized on-farm trials give similar yields to those estimated by farmers. The use of fertilizer doubles average rice yields in on-farm trials to an average of 3.4 t/ha.

Farmer recall yields are higher in Western Region (2.2 t/ha) than in North and Central regions, where yields are between 1.6 and 1.7 t/ha on average. The cost of production surveys of the APEP and LEAD projects indicate highest yields in the Montane system at 3.5 t/ha, with lower yields in the banana-finger millet-cotton farming system (3.0 t/ha), and lowest yields in the Teso, banana-coffee, and unimodal rainfall farming systems (2.0 t/ha)

Rice yield estimates were not included in the agricultural censuses of 1990/91 and earlier. Average yields reported in the UNHS increased from 0.9 t/ha in 1999/2000 to 1.5 t/ha in 2005/06, whereas MAAIF estimates the national average sorghum yield at 1.4 (1.2 to 1.5) t/ha for the period 1970–2009. Rice yield estimates in the 2005/06 UNHS and by MAAIF are similar to farmer recall and on-farm trial estimates as reported in other studies.

### *Sorghum*

In farm surveys, farmers estimate average unfertilized sorghum yields at 1.2 (range of 0.3 to 2.3) t/ha for both local and improved varieties. The 2005/06 UNHS estimates that the majority of sorghum fields in Uganda, 67 percent, are planted as a pure stand (UBOS 2007). Unfertilized local varieties in on-farm trials have similar yields as in farmer reports (1.2 t/ha). The use of improved varieties and fertilizer more than doubles average sorghum yields in on-farm trials to about 2.7 t/ha.

Farmer recall yields are lowest for Central Region (1.0 t/ha), followed by Northern (1.1 t/ha). Western Region sorghum producers have the highest yields at an average of 1.6 t/ha.

Average sorghum yield estimates reported by the agricultural censuses and annual surveys increase from 0.7 (0.2 to 1.6) t/ha in 1965 to 1.9 (1.0 to 2.8) t/ha in 1990/91. Average yields reported in the UNHS were 0.7 t/ha in 1999/2000 and 0.5 t/ha in 2005/06, whereas MAAIF estimates the national average sorghum yield at 1.1 (1.1 to 1.6) t/ha for the period 1970–2009.

Sorghum yield estimates in the UNHS are on the low side of the yield range reported by Ugandan farmers, whereas sorghum yield estimates reported in the 19990 census are on the high side. Yield estimates reported by MAAIF are in the same yield range as farmer reports.

### *Finger Millet*

In farm surveys, farmers estimate average unfertilized finger millet yields at 1.2 (range of 0.3 to 2.7) t/ha for, most likely, local varieties. According to the 2005/06 UNHS, estimates of the percentage of millet fields that are planted as a pure stand vary from 27 to 75 percent between regions (UBOS 2007). Curiously, unfertilized yields of improved millet varieties in on-farm trials are 25 percent lower than farmer recall estimates: 0.9 (0.5 to 1.6) t/ha. The use of fertilizer more than doubles average finger millet yields in on-farm trials to 2.2 t/ha.

Farmer recall yield estimates are lowest for Central and Northern regions at 0.8 and 0.9 t/ha, respectively, and much higher in Western Region at 1.6 t/ha. Unfertilized yields reported in the cost of production surveys by the APEP and LEAD projects show a narrower yield range (1.2 to 1.6 t/ha), with highest yield estimates obtained for the banana-coffee and Montane systems in Western Region (pers. comm., P. Wathum, USAID/LEAD).

Average finger millet yield estimates reported by the agricultural censuses and annual surveys increase from 1.1 (0.4 to 1.8) t/ha in 1965 to 1.5 (0.5 to 3.4) t/ha in 1990/91. With an average national millet yield of 1.5 (1.1 to 1.8) t/ha, the MAAIF estimate for 1970–2009 is very similar. However, estimates of the 1999/2000 and 2005/06 UNHS are much lower at 0.6 and 0.7 t/ha, respectively. Average finger millet yield estimates as reported in the agricultural censuses and by MAAIF are within the yield range reported by farmers in other studies, though somewhat on the high side. Estimates by the UNHS are much lower than farmer recall estimates from other studies.

### *Banana*

In farm surveys, farmers estimate average unfertilized banana yield at 7.4 (range of 1.2 to 25.8) and 8.0 (6.4 to 10.9) t/ha for local and improved varieties, respectively. However, it should be noted that the observed yield range between studies is very wide for local varieties. Yield estimates that are obtained from existing farmer fields using farmer records or allometric methods at an average of 14.1 (6.6 to 25.5) t/ha, are about twice as high. This may be an indication that farmer recall is not the most appropriate method to estimate banana yields. Yield estimations from on-farm trials range from 16.2 t/ha for local varieties to 22.6 t/ha for improved varieties. Fertilizer use on local varieties slightly increased average yields in on-farm trials to 16.5 t/ha, although this figure is based on a few studies only.

Both farmer recall estimates and yield estimates obtained from existing farmer fields using farmer records or allometric methods show clear regional yield differences. Highest yield estimates are found in Western Region (10.8 and 16.3 t/ha for farmer recall and other methods, respectively), while Central and Northern regions have the lowest yields at 6.0 and 8.7 t/ha for farmer recall and other methods, respectively.

All national data show a decline in banana yields over time. Average banana yield estimates reported by the agricultural censuses decrease from 8.1 (5.3 to 11.9) t/ha in 1965 to 5.9 (2.4 to 9.0) t/ha in 1990/91, while estimates by the UNHS decrease from 3.8 in 1999 to 3.0 in 2005/06. The average national banana yield as estimated by MAAIF for the 1970 to 1979 period was 7.3 t/ha, whereas the national average stood at 5.7 t/ha from 1980 to 2009. Recent banana yield estimates by UBOS and MAAIF are lower than farmer recall estimates and much lower than yield estimates obtained from farmer fields using farmer records or allometric models.

### *Cassava*

In farm surveys, the average unfertilized cassava yields estimated by farmers is 6.3 (range of 2.6 to 12.7) t/ha for primarily local varieties. According to the 2005/06 UNHS, estimates of the percentage of cassava fields that are planted as a pure stand vary widely (38 to 74 percent) between regions (UBOS 2007). Due to better management and pure stand planting, yield estimations from on-farm trials range from 12.5 t/ha for local varieties to 12.9 t/ha for improved varieties. Fertilizer use on local and improved varieties increased average yields in on-farm trials to 14.4 and 23.1 t/ha, respectively.

Both farmer recall estimates and estimates from the cost of production surveys of the APEP and LEAD projects indicate that highest cassava yields are found in eastern Uganda (7.0 and 9.9 t/ha, respectively). However, yield levels estimated in other regions are not sufficiently consistent to rank them.

National data on cassava vary strongly between sources. The 1990/91 agricultural census estimated average cassava yield at 25.2 (10.2 to 37.2) t/ha, whereas the 1999/2000 and 2005/06 UNHS surveys present estimates of 3.0 and 1.6 t/ha, respectively. MAAIF estimates the average national cassava yield at 8.2 (4.3 to 14.4) t/ha.

Yield estimates of the 1990/91 census are much higher than farmer recall estimates and even higher than fertilized yields of improved varieties in on-farm trials. This is likely due to the method used (crop cut in a subplot, whereby the obtained yield data were extrapolated to an annual basis to account for multiple harvests). Yield estimates by UNHS are much lower than farmer recall estimates. MAAIF estimates are within the same range as farmer recall estimates.

### *Sweet Potato*

In farm surveys, farmers estimate average unfertilized sweet potato yield at 4.6 (range of 3.2 to 6.5) t/ha for local varieties. According to the 2005/06 UNHS, sweet potato is mainly (71 to 98 percent) grown as a pure stand (UBOS 2007). Due to better management, yield estimates from on-farm trials are 8.5 (3.5 to 13.4) and 10.1 (8.1 to 12.0) t/ha for local and improved varieties, respectively. Curiously, fertilizer use decreased average sweet potato yields to 6.6 t/ha (data from one country-wide study only).

Farmer recall data show lowest sweet potato yields in Northern Region (4.2 t/ha) and highest yields in Eastern (5.2 t/ha). In contrast, the cost of production surveys of the APEP and LEAD projects report lowest yields in the pastoral and Teso farming systems (5.1 and 5.7 t/ha) and highest yields in the unimodal rainfall system (8.1 t/ha).

Average sweet potato yield estimates reported by the agricultural censuses increase from 7.4 (5.5 to 8.8) t/ha in 1965 to 8.4 (5.1 to 11.2) t/ha in 1990/91. Average yield estimates reported in the UNHS decrease from 4.3 t/ha in 1999 to 2.6 t/ha in 2005/06, whereas MAAIF estimates the national average sweet potato yield at 4.3 (3.5 to 4.5) t/ha for the period 1970–2009.

Average estimates from the 1990/91 census for sweet potato yield are above the yield range reported by farmer recall in on-farm surveys. Estimates in the 1999/2000 UNHS and by MAAIF are very close to farmer recall estimates, whereas the 2005/06 UNHS estimates are significantly below the farmer recall sweet potato yield estimates.

### *Irish Potato*

In farm surveys, farmers estimate average unfertilized Irish potato yield at 6.0 (range of 2.5 to 9.0) t/ha for what are likely to be mainly local varieties. According to the 1999/2000 UNHS, Irish potato is primarily (75 to 100 percent) grown as a pure stand (UBOS 2002). Only three on-farm trial studies were found, which reported yields of 12.4 t/ha for fertilized local varieties, 21.6 t/ha for unfertilized improved varieties, and 17.6 t/ha for fertilized improved varieties.

The available data on Irish potato do not allow for a regional analysis in yield trends. The 1990/91 agricultural census estimated national average Irish potato yield at 8.4 (5.0 to 10.9) t/ha, whereas the 1999/2000 and 2005/06 UNHS surveys present estimates of 3.1 and 3.3 t/ha, respectively. MAAIF estimates the average national Irish potato yield at 7.0 (6.8 to 7.1) t/ha. Average estimates from the 1990/91 census and MAAIF for Irish potato yields are in the same range as farmer recall estimates from other studies. Estimates in the UNHS are much lower than average farmer recall estimates.

### *Groundnut*

In farm surveys, farmers estimate average unfertilized groundnut yield at 0.6 (range of 0.2 to 0.8) and 0.8 (0.6 to 0.9) t/ha for local and improved varieties, respectively. According to the 2005/06 UNHS, 39 to 64 percent of the groundnut fields in Uganda are intercropped (UBOS 2007). Only two studies with on-farm trials on groundnuts were found. These report 0.8 t/ha for unfertilized local varieties and 1.6 t/ha for fertilized improved varieties.

Yields as determined by farmer recall are lowest in the Central Region (0.5 t/ha) and highest in the Northern (0.9 t/ha). However, the cost of production surveys of the APEP and LEAD projects indicated that Northern Region had the lowest groundnut yields (0.7 t/ha), while highest yields were estimated for Eastern Region (1.1 t/ha)

The agricultural censuses and annual agricultural statistical surveys estimated groundnut yields in Uganda at 0.9 to 1.1 t/ha. Estimates of the UNHS surveys and MAAIF estimates are lower, in the range of 0.6 to 0.8 t/ha. Estimates of the UNHS and MAAIF are in the same range as farmer recall estimates in other studies. Estimates of the agricultural censuses are above the yield range indicated by farmer recall studies.

### *Bean*

In farm surveys, farmers estimate average unfertilized bush bean yields at 0.9 (range of 0.4 to 2.3) and 1.1 (0.9 to 1.2) t/ha for local and improved varieties, respectively. According to the 2005/06 UNHS, beans are a common intercrop in farm fields–59 to 92 percent of the bush bean fields in Uganda are intercropped (UBOS 2007). Average yield estimates of unfertilized local bush bean varieties in on-farm trials were similar to those of farmer estimates at 0.9 t/ha. Notably, improved varieties yielded only 0.8 t/ha on average in on-farm trials when unfertilized.

Farmer recall yields are lowest in Central and Northern regions at 0.8 t/ha and highest in Western Region (1.1 t/ha). The cost of production surveys of the APEP and LEAD projects also indicated that the unimodal rain farming system of Northern Region had the lowest bush bean yields (0.6 t/ha). Highest yields were estimated for the banana-finger millet-cotton farming system of central region, where average yields were estimated at 1.5 t/ha.

Average bush bean yield estimates reported by the agricultural censuses and annual surveys increase from 0.6 (0.4 to 0.8) t/ha in 1965 to 1.4 (0.6 to 2.4) t/ha in 1990/91. Estimates of the UNHS surveys and MAAIF are 0.8 t/ha and 0.6 (0.4 to 0.8) t/ha, respectively. Estimates of the UNHS and MAAIF are in the same range as farmer recall estimates in other studies. Estimates of the 1990/91 agricultural census on the high side of the yield range indicated by farmer recall studies.

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